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THE JOURNAL
OF THE
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Volume 16 Number 4

APRIL • 1945

Acoustic Intensity Distribution from a "Piston" Source

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Brown University, Providence, Rhode Island

(Received January 30, 1945)

INTRODUCTION

THE theoretical intensity distribution in an acoustic beam from a circular piston-like source has been analyzed previously, in a number of ways. A treatment like that in optics of Fraunhofer diffraction for a circular aperture[1] attains only limited success, leading to results invalid except at very great distances. An exact expression for the intensity along the axis of the beam has been derived from Rayleigh's general integral for the velocity potential at any point.[2] Lindsay[3] has found an approximate equation for the intensity at points on a cylindrical surface which if extended back would have the piston for its base, but this result is limited in generality and its accuracy is not certain. Backhaus,[4] by expanding Rayleigh's expression in spherical harmonics, set up a formal general solution which may be useful for small pistons or long wave-lengths, but is hopelessly unwieldy for other cases. This would be expected from the use of spherical functions, suited to a widely divergent beam, but not to the narrow beam characteristic of high frequency supersonics from a relatively large source.

In this paper a fairly simple and accurate approximation is derived which holds at points near the axis of a narrow beam, for certain ranges of wave-lengths and piston sizes. Some experimental evidence is adduced to support it.

DERIVATION OF THE EQUATION

Let us consider a flat circular piston of radius a, setting up harmonic acoustic vibrations normal to its surface; we choose cylindrical coordinates with the z axis perpendicular to the piston at its center, and with r normal to z. The velocity potential $\phi(r, z, t)$ which governs the intensity can be written as $\phi = e^{i\omega t}F(r, z)$. The wave equation in r, z, and t (which the velocity potential satisfies) becomes

$$c^2\left[\frac{\partial^2}{\partial r^2}(e^{i\omega t}F)+\frac{1}{r}\frac{\partial}{\partial r}(e^{i\omega t}F)+\frac{\partial^2}{\partial z^2}(e^{i\omega t}F)\right]=\frac{\partial^2}{\partial t^2}(e^{i\omega t}F),$$

or

$$\frac{\partial^2 F}{\partial r^2}+\frac{1}{r}\frac{\partial F}{\partial r}+\frac{\partial^2 F}{\partial z^2}=-(\omega^2/c^2)F=-k^2F. \quad (1)$$

[1] See, e.g., R. B. Lindsay, Phys. Rev. **32**, 518, 519 (1928).
[2] See, e.g., G. W. Stewart and R. B. Lindsay, *Acoustics* (D. Van Nostrand Company, Inc., New York, 1930), p. 251 ff.
[3] R. B. Lindsay, Phys. Rev. **32**, 515–519 (1928).
[4] H. Backhaus, Ann. d. Physik **5**, 1 ff (1930).

The angular frequency is denoted by ω and the wave velocity by c.

If a solution of the wave equation has the form $e^{i\omega t}F(r, z)$, F can be expanded in a power series in r. The coefficients are functions of z, and are in fact uniquely related to the axial values of F. This is simply an extension of a well known fact concerning harmonic functions. This is shown as follows.

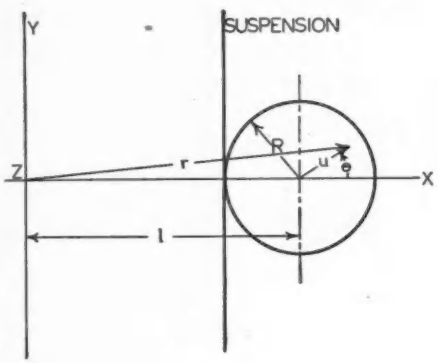

FIG. 1.

Let

$$F(r, z)=A_0(z)+A_2(z)r^2+A_4(z)r^4+\cdots.$$

Substituting this series into (1), we find

$$A_2=-\frac{1}{2^2}\left(A_0k^2+\frac{d^2}{dz^2}A_0\right),$$
$$A_4=+\frac{1}{2^24^2}\left(A_0k^4+2k^2\frac{d^2}{dz^2}A_0+\frac{d^4}{dz^4}A_0\right). \quad (2)$$

Since the axial value of F, $F(0, z)$, equals $A_0(z)$, we go to an earlier reference[3] for the exact value of this space part of the velocity potential along the central axis; to within multiplying constants:

$$F(0, z)=A_0(z)\propto i\{\exp[-ik(z^2+a^2)^{\frac{1}{2}}]-e^{-ikz}\}. \quad (3)$$

We can evaluate the necessary derivatives of $A_0(z)$ from (3) for use in (2). This can be done more easily by considering only the case where $z\gg a$, so that $(z^2+a^2)^{\frac{1}{2}}$ can be expanded by the binomial theorem. We also require that the product $a\cdot k$ shall not greatly exceed z. These restrictions allow rejection of various demonstrably small terms, and lead to the result:

$$F(r, z)\propto ie^{-ikz}\left\{\exp[-ik(a^2/2z-a^4/8z^3)]\times\left[1-\frac{a^2k^2r^2}{4z^2}+\left(\frac{a^4k^4}{64z^4}+\frac{ia^2k^3}{16z^3}\right)r^4\right]-1\right\}. \quad (4)$$

The excess pressure, p, in an acoustic wave is proportional to $id\phi/dt$. Therefore

$$p\propto ie^{i\omega t}F(r, z). \quad (5)$$

By substituting the results of (4) into (5) and computing p_r (the real part of p) in the usual way, we find

$$p_r\propto\{[\cos(\omega t-kz)][M\cos B+N\sin B-1]+[\sin(\omega t-kz)][M\sin B-N\cos B]\}, \quad (6)$$

with the abbreviations

$$M=1-\frac{a^2k^2r^2}{4z^2}+\frac{a^4k^4r^4}{64z^4},\quad B=k\left(\frac{a^2}{2z}-\frac{a^4}{8z^3}\right),$$
$$N=\frac{a^2k^3r^4}{16z^3}.$$

Next we square (6) and average over one cycle, since the acoustic intensity is proportional to the average square of the excess pressure. If we ignore powers of r higher than the fourth and reject any terms which are relatively small because of their combinations of a, k, and z, the following expression for the intensity I results:

$$I\propto\overline{p_r^2}\propto\left(\sin^2\frac{ka^2}{4z}\right)\left(1-\frac{a^2k^2}{4z^2}r^2+\frac{a^4k^4}{64z^4}r^4\right). \quad (7)$$

The behavior of the polynomial in (7) depends on a, λ, and z, since $k=\omega/c=2\pi/\lambda$. Under the conditions stipulated just prior to (4), the terms in r^2 and r^4 are small for $r<1$ cm, and sometimes for larger values of r.

The root-mean-square excess pressure, which represents the average amplitude of the acoustic pressure, can be found from (7):

$$p_{\text{rms}}\propto I^{\frac{1}{2}}\propto\left(\sin\frac{ka^2}{4z}\right)\left(1-\frac{a^2k^2}{8z^2}r^2\right). \quad (8)$$

This is true because the trinomial in (7) is a

perfect square, so that there is no r^4 term in (8). Thus, within the proper range of λ and z, and for points near the axis, a curve of measured root-mean-square pressure *vs.* r at fixed z would be a parabola, out to values of r for which the neglected r^6 term finally becomes appreciable. The equation of this parabola will be abbreviated hereafter as $\alpha-\beta r^2$ with

$$\beta/\alpha=(a^2k^2)/(8z^2). \tag{9}$$

If, instead, a curve of measured *intensity vs.* r were plotted, it too would be parabolic within a rather smaller range of r, having the approximate form $\alpha^2-2\alpha\beta r^2$. From its shape we can easily compute α and β for the root-mean-square pressure equation. The term β^2r^4 can be taken into account if its size is appreciable.

The experimental evidence mentioned was found at frequencies in the general region of 1 megacycle, in water. The radius a of the flat circular "piston" source (piezoelectric quartz crystal) was 1 cm. Values of k ranged from about 20 to 50 cm^{-1}, so that z should be about this magnitude also. Under such conditions measurements can be taken with a radiometer or torsion disk, the response of which is proportional to *intensity*, or a piezoelectric microphone, where the response is proportional to root-mean-square *pressure*. Unfortunately neither radiometer nor microphone can be made small enough to detect the point-to-point values, in a narrow beam. Therefore we must consider the necessary corrections before quoting results.

CORRECTIONS FOR THE RADIOMETER

A conventional type of acoustic radiometer[5] uses a small hollow "pill-box" structure, supported at one edge by a stretched suspension of the galvanometer type (Fig. 1). The *radiation pressure* exerted on such a disk is proportional to the acoustic intensity,[5] and this pressure produces a torque which deflects the disk. Null readings are taken by twisting the disk back to its original position, nearly perpendicular to the beam. These readings are found as a function of the disk's position in the beam, and the problem is to deduce therefrom the point-to-point intensity variation.

[5] L. Bergmann, *Ultrasonics* (G. Bell & Sons, Ltd., London, 1938), pp. 44–47.

Figure 1 shows the disk as it might appear when viewed from the piston source. The y-axis is vertical, as is the suspension fiber. We assume that the disk has been adjusted by trial so that its center is on a level with the beam axis z. The distance l is variable at will by the experimenter. We denote an area element on the disk as $dxdy$ or $ududθ$ as necessary. For any plane in which $z=$constant, the radiation pressure P is a function of r only, or $P(r)=P(x^2+y^2)$. The element of torque exerted about the suspension by this pressure at the point x, y (or l, u, θ) is*

$$dT=P(r)(x-l+R)dxdy. \tag{10}$$

In accordance with (9) ff, we assume $P(r)\propto(\alpha^2-2\alpha\beta r^2)$. Then (10) takes the form

$$dT\propto(\alpha^2-2\alpha\beta x^2-2\alpha\beta y^2)(x-l+R).$$

After transformation to u and θ, using $x=l+u\cos\theta$, $y=u\sin\theta$, the equation is readily integrated to yield

$$T(l)\propto\pi R^3[\alpha^2-2\alpha\beta l^2-2\alpha\beta(R^2/2)-2\alpha\beta lR/2].$$

If we substitute $x'=l+R/4$,

$$T(x')\propto[(\alpha^2-7\alpha\beta R^2/8)-2\alpha\beta x'^2]. \tag{11}$$

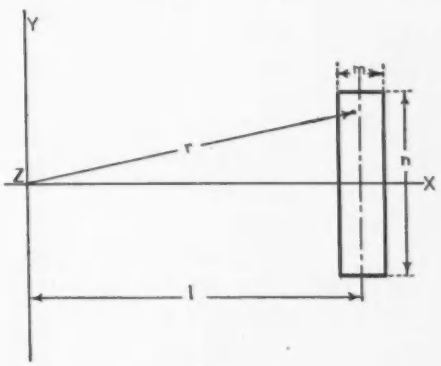

FIG. 2.

Readings of torque T as a function of distance l measured along the x axis from any arbitrary origin then plot as a parabola in terms of x'. Since R is known, from such an experimental curve α and β can readily be found to within a constant factor which we ignore. From these values, β/α can be computed for comparison with (9).

* Possible effects of oblique incidence should be negligible, for Eq. (11) is not expected to hold except near the axis.

CORRECTIONS FOR THE MICROPHONE

The Rochelle salt microphone used was developed by one of the authors.[6] It responds to root-mean-square pressure, so the only correction required is for the finite size of the sensitive

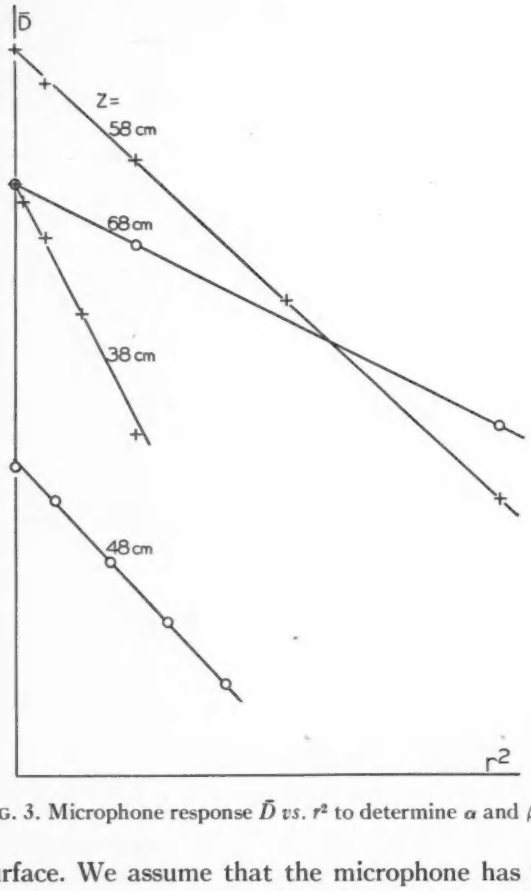

FIG. 3. Microphone response $\bar{D}$ *vs.* r^2 to determine α and β.

surface. We assume that the microphone has a flat face m cm by n cm (Fig. 2), parallel to the plane of the source, and uniformly sensitive in all parts. It is sketched in Fig. 2, in a position corresponding to that of the disk in Fig. 1, centered similarly on the x axis. Let the response of the microphone be D, proportional to p_{rms}. The average value of D over the surface is

$$\bar{D} \propto \overline{p_{\text{rms}}} = \frac{1}{mn} \int\int p_{\text{rms}}(r)\,dxdy, \qquad (12)$$

which from (9) becomes

$$\bar{D} \propto \frac{1}{mn} \int\int (\alpha - \beta r^2)\,dxdy,$$

or

$$\bar{D} \propto \left[\frac{\alpha}{mn} \int\int dxdy - \frac{\beta}{mn} \int\int r^2 dxdy \right].$$

The first integral is simply mn, and the second is the moment of inertia, about the z-axis, of a flat plate with unit surface density. Thus

$$\bar{D} \propto \left\{ \alpha - [\beta/mn] \left[mn \left(\frac{m^2+n^2}{12} + l^2 \right) \right] \right\},$$

or

$$\bar{D} \propto \left[\left(\alpha - \frac{m^2+n^2}{12} \beta \right) - \beta l^2 \right]. \qquad (13)$$

Here again if the response $\bar{D}$ is plotted as a function of distance l along the x-axis, from an arbitrary origin, the resulting curve is a parabola. From this, a replotting of $\bar{D}$ *vs.* r^2 allows determination of β and of $[\alpha - (m^2+n^2)\beta/12]$—hence of α and β/α. Of course m and n are assumed known, from direct measurements. Figure 3 shows the results of replotting response *vs.* r^2 for four distances (microphone data in Table I).

RESULTS OF COMPARISONS

As a further check, the expression derived by Lindsay* for the intensity at $r=a$ was evaluated for the same a, z, k. Then a parabola was fitted at two points—the maximum intensity (on the axis, from Eq. (7)) and the result of Lindsay's equation at $r=a$. The values of β/α thus computed are included in Table I.

All measurements were made in water at room temperature. The figures in parentheses in the "β/α exp" column are the values which result from ignoring the microphone corrections.

TABLE I. β/α as a function of z, k.

z	β/α (exp.)	β/α (theo.)	theo./exp.	β/α (Lindsay)
38 cm	0.037	0.040	0.93	0.040
48	0.025	0.025	1.00	0.024
58	0.016	0.017	0.94	0.016
(Freq. 500 kc, radiometer radius 0.5 cm)				
38	0.218(0.224)	0.212	0.97	0.197
48	0.150(0.154)	0.133	0.89	0.127
58	0.090(0.092)	0.091	1.01	0.087
68	0.055(0.055)	0.066	1.20	0.065
(Freq. 1150 kc, microphone $m=0.3$ cm, $n=1.2$ cm)				

[6] L. W. Labaw, J. Acous. Soc. Am. **16**, 100 (1944).

* $I \propto \{1 - 2J_0(a^2k/z) \cos(a^2k/z) + [J_0(a^2k/z)]^2\}/16$, the same multiplying constants being omitted here as in our (7).

APPROXIMATE SIZE OF RADIATION CONE

An approximate idea of the spread of an acoustic beam can be given by stating the half-angle of a cone on the surface of which the intensity falls to one tenth of its axial value at the same z. This half-angle can be expressed as arctan r_0/z, and for any particular value of z is determined by r_0, the radius at which the intensity falls to one tenth its axial value. Equation (7) can be solved very easily for this value of r_0:

$$1-\frac{a^2k^2}{4z^2}r_0^2+\frac{a^4k^4}{64z^4}r_0^4=0.1,$$

or

$$r_0=2.32z/ak=0.373\lambda z/a. \qquad (14)$$

Lindsay[3] attacked the same problem and derived an expression which reduces to $r_0=0.45\lambda z/a$. He also showed that the Fraunhofer diffraction treatment leads to $r_0=0.435\lambda z/a$.

For all cases mentioned in Table I, such calculations have been made for comparison with experiment. This is subject to experimental uncertainty because radiometer and microphone corrections as derived above hold only for the parabolic part of the response curve, while the intensity falls to $\frac{1}{10}$ (amplitude to $1/\sqrt{10}$) beyond this; therefore, only moderately satisfactory corrections can be made.

DISCUSSION

The occasional wide discrepancies in Table I between theoretical and experimental values of β/α are probably caused by experimental difficulties, either in failure of the source to approximate a piston closely or in faults of the experimental method. The data were so taken that each of the quoted results is deduced from the average of a large number of readings, individually quite consistent (compare Fig. 3). Still, other experience with the method showed some unexplained variations in runs taken under apparently identical conditions. In the case of worst disagreement (microphone, 68 cm), the experimental curve is relatively low and broad, and fitting it with a parabola is subject to considerable uncertainty.

TABLE II.

z	r_0 (Eq. (14))	r_0 (exp.)
38 cm	4.13 cm	4.25
48	5.23	5.5
58	6.3	6.9
	(Freq. 500 kc. Radiometer)	
38	1.80	1.85
48	2.28	2.30
58	2.75	2.79
68	3.22	3.60
	(Freq. 1150 kc. Microphone)	

The rather close correspondence between β/α values computed by the present method and by Lindsay's, and the extremely good agreement with experiment in three cases out of seven strongly suggest that experimental errors cause the larger discrepancies. It must be admitted, however, that on the basis of other evidence the results taken with the microphone were regarded from the experimental point of view as much more significant and reliable than the radiometer data, even though the latter appear to afford a somewhat better check with theory.

The validity of the microphone corrections is supported by Table I; omitting the corrections causes poorer agreement. Since the intensity curves at 500 kc are relatively broad and the radiometer disk small, exclusion of the radiometer corrections does not materially affect these comparisons.

Lindsay's equation for the acoustic intensity is evidently somewhat inferior to the present one, particularly at higher frequencies and shorter distances. We again emphasize that his method gives only two points on the intensity curve, at $r=0$ and $r=a$, so that fitting a parabola is of doubtful significance. As Fig. 3 shows, a parabola fits the experimental data very well, even when the resulting constants do not agree well with the theory.

The results of Table II are gratifying, since it was not originally suspected that (7), (8) could hold for such large values of r. The sizes of the discrepancies are to be expected, but the reason for their directions is not so obvious. Since the r^6 term which was omitted from (7) is negative, its inclusion would make the theoretical r_0 even smaller than now. Thus the disagreement must be due to other shortcomings in theory (e.g., still higher powers of r) or experiment. It is to be noted that the rather large discrepancy in Table I, 1150 kc, at $z=48$ cm, is not matched by similar difficulties in Table II. Certainly the

theoretical results must break down badly just beyond r_0, since (7), (8) are inadequate to explain the diffraction maxima and minima which begin there. Evidently the change in shape of the experimental curves necessary to produce a minimum (not zero) and subsequent maximum would be just such as to explain these discrepancies.

Particularly for the higher frequency and for smaller z neither the Fraunhofer diffraction treatment nor Lindsay's equation leads to as good agreement for r_0. Even in the worst cases of Table II, these other expressions for r_0 lie about equally far on the other side of the experimental values. Their failure may easily be explained: Fraunhofer diffraction does not occur, even very approximately, at the present values of z; the approximate conical beam predicted by the several methods does not continue in as far as $r=a$.

We conclude (1) that the general agreement shown above definitely supports the microphone point-to-point corrections deduced here; (2) that (7), (8) are adequate to describe the acoustic amplitude and intensity curves from a circular pistonlike source, within the stated ranges of size, distance, and wave-length, out to values of r in excess of the piston radius, and for narrow beams almost to the first diffraction minimum; (3) that the present equations have certain advantages of simplicity, generality, or accuracy over the Fraunhofer method and the equations of Backhaus and of Lindsay.

The authors wish to acknowledge indebtedness to H. P. Gauvin, in the course of whose Senior thesis many of the quoted measurements were made, and to J. L. McHale, Jr. who in a Senior thesis checked and elaborated some of the theoretical analysis.

Curved Quartz Crystals as Supersonic Generators*

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(Received February 14, 1945)

The supersonic beam radiated from a one-centimeter radius X-cut quartz disk is examined experimentally as a function of the spherical curvature of the crystal, at a frequency of 1110 kilocycles. The crystals of large curvature produce a definite focusing action as has been reported from an earlier investigation. The experimental data show that it is possible to obtain a much greater excess pressure amplitude close to the generator from a curved crystal than is possible from a flat crystal having the same area and thickness using the same input power. The quartz plates of small curvature do not produce a marked focusing action but give a larger supersonic amplitude at large distances from the generator. The flat crystal gives the smallest angle of spread of the supersonic beam. The resonant frequency for any of the five crystals studied did not differ by more than 20 kilocycles (2 percent) from that to be expected from the thickness.

INTRODUCTION

TWO types of problems are of particular interest concerning the supersonic beam generated by a piezoelectric crystal or mosaic of such crystals: (1) the production of a large supersonic intensity at small distances from the generator to be utilized in studying the thermal, chemical, and biological effects it produces, and (2) the maintainment of as nearly constant measurable intensity as possible over large distances along the direction of propagation of the beam traveling in a free field.

A solution to the first and second problem is obviously to increase the electrical power put into the generator. This has limitations set by the dielectric and mechanical properties of the crystals and the dielectric properties of the medium surrounding the crystals. Greutzmacher used another method[1] as a solution to the first problem; namely to concentrate the supersonic energy by using a spherically curved source of rather large curvature. His examination of the supersonic beam thus generated was not very precise and could well be the subject of further investigation. Crystal sources which have only a slight curvature were at first thought by the author to offer a solution to the second problem by confining the radiation within a smaller solid angle than could be accomplished by using the flat crystal at any one frequency. This was based on a consideration of the lines defining the extremities of the beam. Any two of these lines are known to intersect near the generator for a flat source,[2] and would intersect near the radius of curvature for the curved crystals if the focusing were similar to that in optics. This would suggest that for crystals of very slight curvature, the focusing might decrease the angle of the beam from that obtained from consideration of a piston source,[2] thereby increasing the range of the energy transmitted.

For a given alternating voltage across the crystals to be studied, the range of the beam, or the intensity at a specific point in front of the generator, depends not only on the angle of spread and hence on the *rate* of decrease of intensity along the axis of the beam but also on the maximum value from which the intensity decreases with the square of the distance. Thus, the intensity produced 50 cm from the generator might be greater for a curved crystal than for a flat crystal even though the angle of spread of the beam from the flat crystal was less than that for the curved one. The shape of, and the position of the operating point on the resonance curves for the different crystals also controls the maximum intensity obtainable at a given distance from any one crystal.

The possible variance among several specimens of quartz should be kept in mind in examining the results to be presented. A similar set of crystals ground in like fashion would undoubtedly

* Presented in part at the New York meeting of the Acoustical Society, May 13, 1944.

[1] J. Greutzmacher, Zeits. f. Physik 96, 342 (1935).

[2] G. W. Stewart and R. B. Lindsay, *Acoustics* (D. Van Nostrand Company, Inc., New York, 1930), p. 253.

show the same trends but the specific inequalities in the results between crystals of different curvature might be changed.

MEASUREMENTS

The supersonic generators were one inch square X-cut quartz crystals on which copper electrodes were plated. The ground potential electrode covered one whole surface of a crystal while the high potential electrode was circular having a radius of one centimeter. Since the voltages placed across the crystals were low (not over 225 volts*) the supersonic beam from these crystals had approximate circular symmetry. This was checked by experimental measurements. The crystals were mounted on a Bakelite holder as shown in Fig. 1. The crystals used were all 90 ± 0.1 thousandths of an inch thick** except the 7-cm radius one which was 89 thousandths and had radii of spherical curvature of ∞, 25, 8, 7, and 4 centimeters. These crystals were attached to the holder at their periphery with a mixture of beeswax and rosin. This holder with the attached crystals was mounted at the center of one end of a tank $3\times3\times20$ feet, filled with water. The ground potential side of a crystal was in the water while the high potential side vibrated in air. The central part of the holder could be rotated from outside the tank to put any crystal desired into a position where measurements could be made. The size of the tank compared to the dimensions of the supersonic beams generated assured very little error caused by reflection.

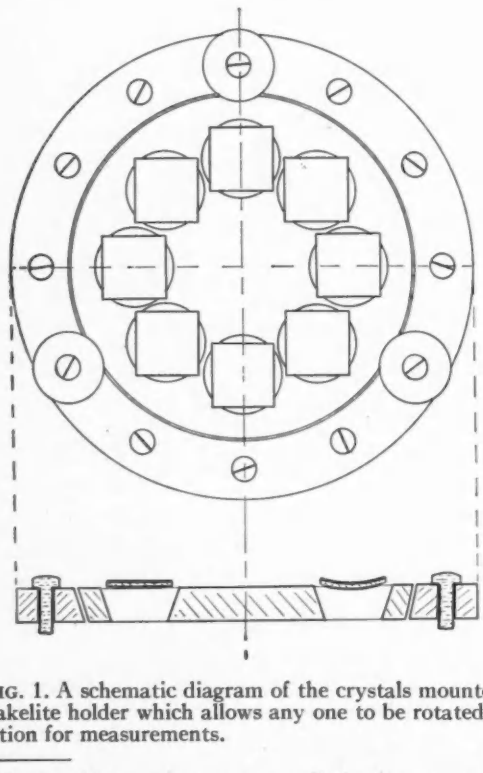

FIG. 1. A schematic diagram of the crystals mounted in a Bakelite holder which allows any one to be rotated into position for measurements.

The detecting device was a small Rochelle salt crystal microphone presenting a circular surface area (perpendicular to the X-crystallographic direction) six millimeters in diameter, to the supersonic beam. This microphone response was amplified by a four stage radiofrequency tuned amplifier and the result read on an output meter. The readings of this meter were taken as the relative excess pressure amplitude in the supersonic beam.

The frequency was kept constant at 1100 kilocycles for all readings except when getting data for the resonance curves of the crystals. The crystals were driven well off resonance since the resonant frequency, according to their thickness should be 1255 kilocycles. The crystals were excited off resonance to eliminate the wide variations in output resulting from small input power fluctuations manifest at resonance.

The purpose of Fig. 2 is to acquaint the reader with the author's notation. The diagram represents four quadrants of the excess pressure amplitude surfaces taken at about 30, 40, 50, and 60 cm, in front of a flat quartz generator of one centimeter radius executing thickness vibrations at 1200 kilocycles. The crystal is drawn to scale according to the distances marked off along the Y and Z axes. The curved lines parallel to the YZ planes are equally spaced in amplitude and represent the intersection of the amplitude surface with planes parallel to the YZ plane. These curves as well as the excess pressure amplitude curves given later, are all subject to a correction for the finite size of the microphone[3] but this is of little moment for the material about which this paper is concerned. The diagram clearly indicates the decrease in the amplitude along the axis of

* This and later references to applied voltage represents peak to peak voltage rather than the root-mean-square.

** The author would be glad to discuss the details of grinding the crystals with anyone interested.

[3] A. O. Williams and L. W. Labaw, J. Acous. Soc. Am. 16, 231 (1945).

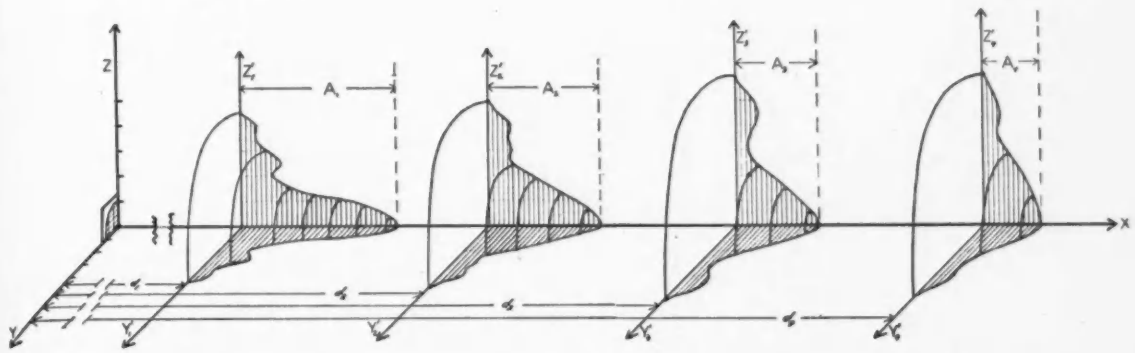

FIG. 2. Quadrants of the supersonic amplitude surfaces generated in water by a flat 1-cm radius X-cut quartz crystal at 30, 40, 50, and 60 cm from the generator when excited to vibrate off resonance at 1200 kilocycles.

the beam as well as the way in which the beam spreads out with increased distance from the crystal. Each of these surfaces represents very nearly the same energy as indicated by roughly integrating the volume enclosed.

Figure 3 shows the behavior of the supersonic beams from five crystals when excited at a frequency of 1110 kilocycles with a peak to peak voltage of 80 volts. The curves represent the relative excess pressure amplitude as measured by the microphone moved along the *Y* direction (Fig. 2). The experimental points were taken at 2 millimeter intervals. Some of the observations which can be made from this data are: (1) all the curved crystals give more intensity near the generator than the flat one; (2) the 4-cm radius crystal shows a definite focusing action as evidenced by the very narrow amplitude curve at 5 cm from the crystal and a rapid decrease in amplitude, at 10 and 20 cm from the generator accompanied by a rapid spread of the beam (curves taken about 3 cm from the generator show a smaller amplitude at the maximum than the one at 5 cm); (3) the maximum amplitude for the infinite and 25-cm radius crystals increased in moving from 5 to 10 cm from the generator, which is undoubtedly the result of more energy striking the microphone in phase at 10 cm rather than there being more energy at 10 cm than at 5; (4) even though there is a marked focusing by the 4-cm radius crystal, the actual maximum amplitude obtainable is not as great as that from the 7- and 8-cm radius crystals at any distance from the generators. One might conclude from this data that it is advantageous to use curved crystals as compared with flat crystals to get a large intensity near the supersonic generator, but if the curvature becomes too great, you lose some of this advantage.

The behavior of the ∞-, 25-, 8-, and 7-cm radius crystals with respect to range is better seen from Fig. 4. The voltage applied to the crystals in this case was 150 volts with all other conditions the same as for the data in Fig. 3 except the distances from the generator at which the measurements were taken. The curves at 20 cm from the crystal have the same shape as those in Fig. 3 but have greater amplitude. The maximum amplitude for both the 7 and 8 cm radius crystals falls off with the distance from the generator at a more rapid rate than that for the 25- and ∞-cm radius crystals. This, coupled with a comparison of the amplitudes for the ∞- and 25-cm radius crystals indicates the greatest range for the 25-cm radius crystal.

The data thus far presented were taken with the crystals concave to the direction of propagation of the beam. It was thought of possible interest to measure the supersonic beam with the convex crystal surface in the water, though its practical significance is doubtful. These results are plotted in Fig. 5, where the voltage applied to the crystal was about 210 volts and the readings were taken at 5, 10, and 20 cm from the generator. The curve for the 4-cm radius crystal at 20 cm from the generator is absent since the amplitude was immeasurably small. There is a suggestion of a split peak in the amplitude curve as the curvature is increased. When vibrating the crystals this way, the supersonic beam generated is no longer symmetrical. The cross section of the amplitude surface in the *XZ* plane differs from

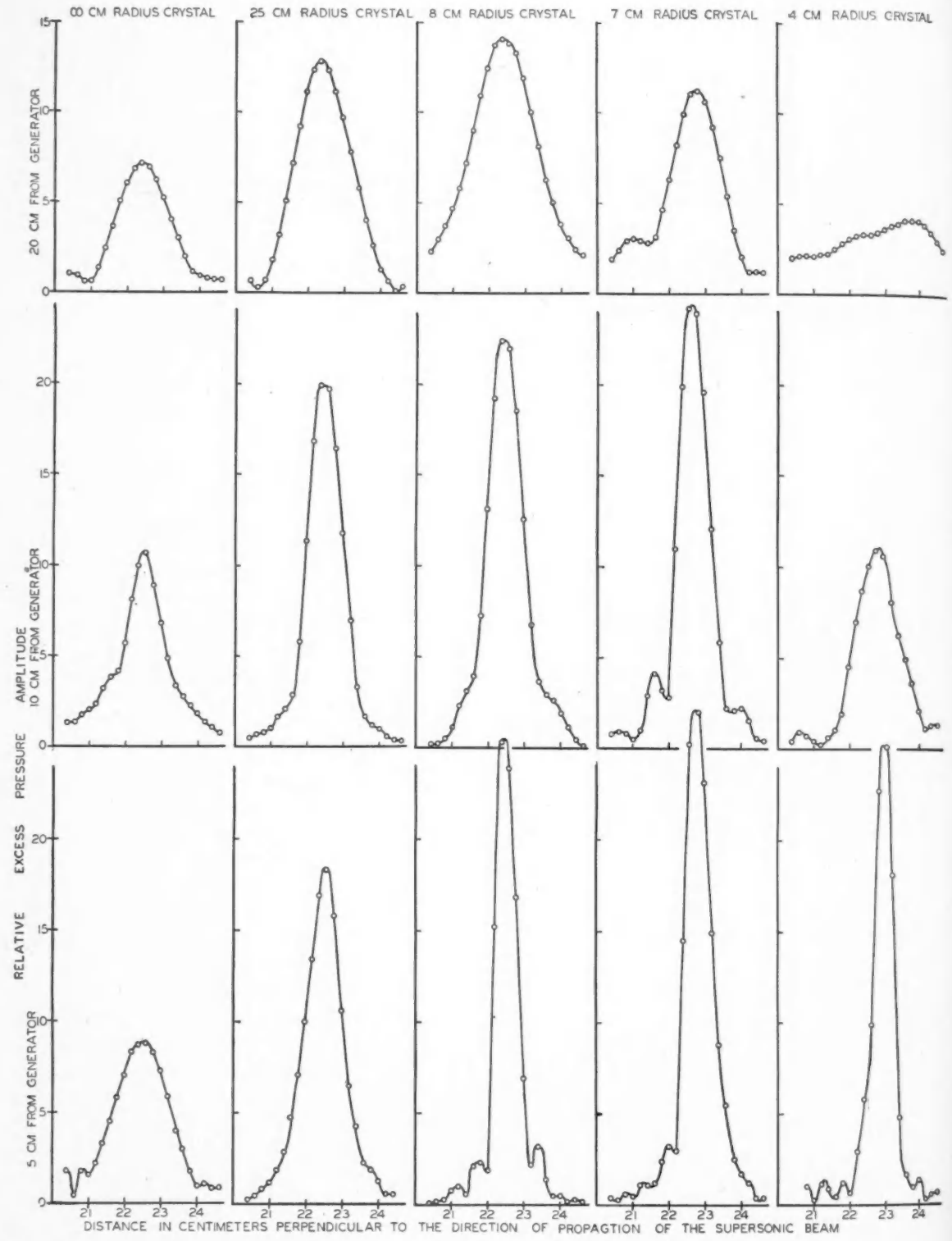
00 CM RADIUS CRYSTAL
25 CM RADIUS CRYSTAL
8 CM RADIUS CRYSTAL
7 CM RADIUS CRYSTAL
4 CM RADIUS CRYSTAL
RELATIVE EXCESS PRESSURE AMPLITUDE
5 CM FROM GENERATOR
10 CM FROM GENERATOR
20 CM FROM GENERATOR
DISTANCE IN CENTIMETERS PERPENDICULAR TO THE DIRECTION OF PROPAGTION OF THE SUPERSONIC BEAM

FIG. 3. The relative excess pressure amplitude in the supersonic beam along the Y direction at 5, 10, and 20 cm from the generator resulting from the excitation of the five crystals at 1110 kilocycles by 80 volts when the curved crystals had the concave side in water.

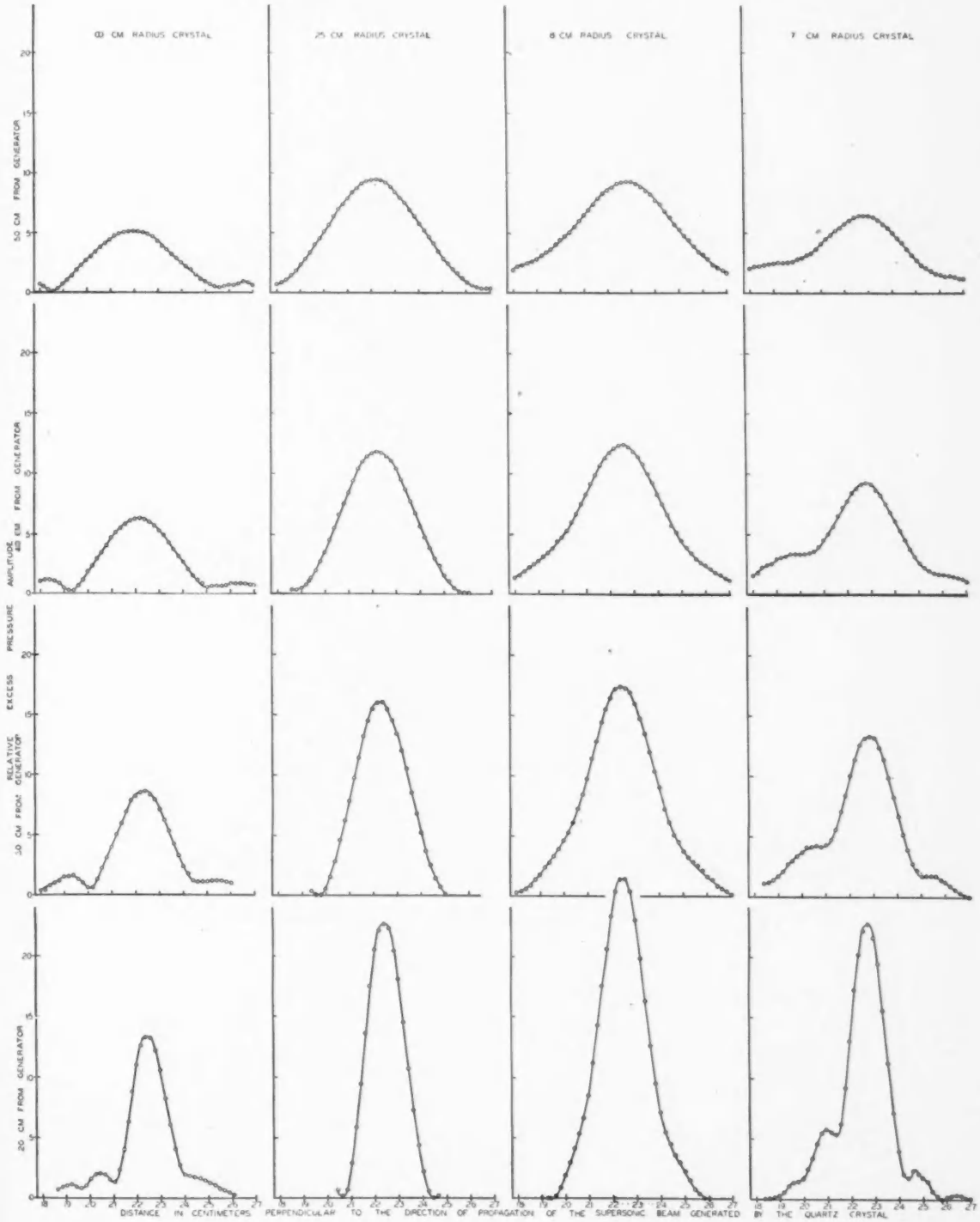
CM RADIUS CRYSTAL
25 CM RADIUS CRYSTAL
8 CM RADIUS CRYSTAL
7 CM RADIUS CRYSTAL
50 CM FROM GENERATOR
40 CM FROM GENERATOR
30 CM FROM GENERATOR
20 CM FROM GENERATOR
RELATIVE EXCESS PRESSURE AMPLITUDE
DISTANCE IN CENTIMETERS PERPENDICULAR TO THE DIRECTION OF PROPAGATION OF THE SUPERSONIC BEAM GENERATED BY THE QUARTZ CRYSTAL

FIG. 4. The relative excess pressure amplitude as in Fig. 3 at 20, 30, 40, and 50 cm from the generator when the impressed signal was 150 volts.

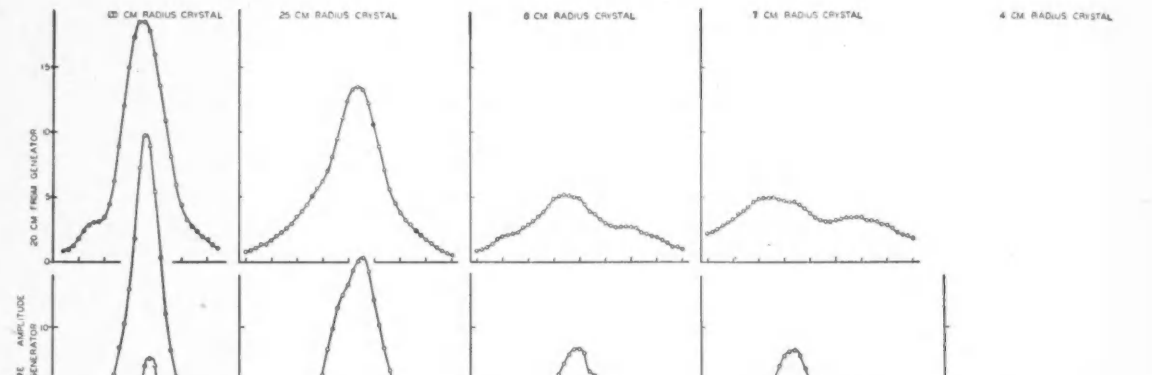
∞ CM RADIUS CRYSTAL
25 CM RADIUS CRYSTAL
8 CM RADIUS CRYSTAL
7 CM RADIUS CRYSTAL
4 CM RADIUS CRYSTAL
20 CM FROM GENERATOR
10 CM FROM GENERATOR
5 CM FROM GENERATOR
RELATIVE EXCESS PRESSURE AMPLITUDE
DISTANCE IN CENTIMETERS PERPENDICULAR TO THE DIRECTION OF PROPAGATION OF THE SUPERSONIC BEAM GENERATED BY THE QUARTZ CRYSTAL

FIG. 5. The relative excess pressure amplitude along the *Y*-axis from the five crystals at 5, 10, and 20 cm from the generator when the curved ones were mounted with the convex side in the water and excited by 210 volts at 1110 kilocycles.

that in the *YZ* plane. The double peak from the 25-cm radius crystal which is evident at 5 cm from the generator but not at 20 cm is undoubtedly due to a lack of phase agreement of all the energy reaching the microphone when it is close to the generator.

ANALYSIS OF RESULTS

The data presented in Fig. 3 and Fig. 4 are summarized graphically in Fig. 6A, B, and C. Figure 6A shows the relative excess pressure amplitude along the axis of the supersonic beam generated by the five crystals as a function of the distance from the source, when the crystals were excited by an electric signal of 150 volts. This shows clearly the different rates at which the amplitude decreases with the distance. It also shows how the maximum amplitude obtainable moves in toward the generator with increased curvature. The maximum for the 4-cm radius crystal occurs somewhere between 3 and 5 cm from the crystal and is very close to 50 on the relative amplitude scale. The maxima of these curves represents to the author the position nearest to the generator at which all the energy reaching the microphone has the same phase. This viewpoint, and the motion of this maximum as the curvature changes, is supported by geometrical considerations, if the vibration of the crystal is perpendicular to the face and is, on the average, in phase.

The angle of spread of the half-width of the amplitude and intensity curves are given in Fig. 6B as a function of crystal curvature. The half-width was chosen as a criterion rather than the width at which the intensity or amplitude has fallen to one-tenth its maximum value as is sometimes done in theoretical considerations, since in this experiment, as is seen in Fig. 4, this latter would give results of questionable value. The two points on each curve for the ∞-cm radius crystal are the result of analyzing the curves in both Fig. 4 and Fig. 5. These results agree qualitatively with those given in Fig. 6A.

The apparent point source of energy can be found from the data in Fig. 3 and Fig. 4 in two ways: (1) by finding the position of the vertex of the angle defining the half widths of the amplitude and intensity curves and (2) by finding the position from which the intensity falls off as the

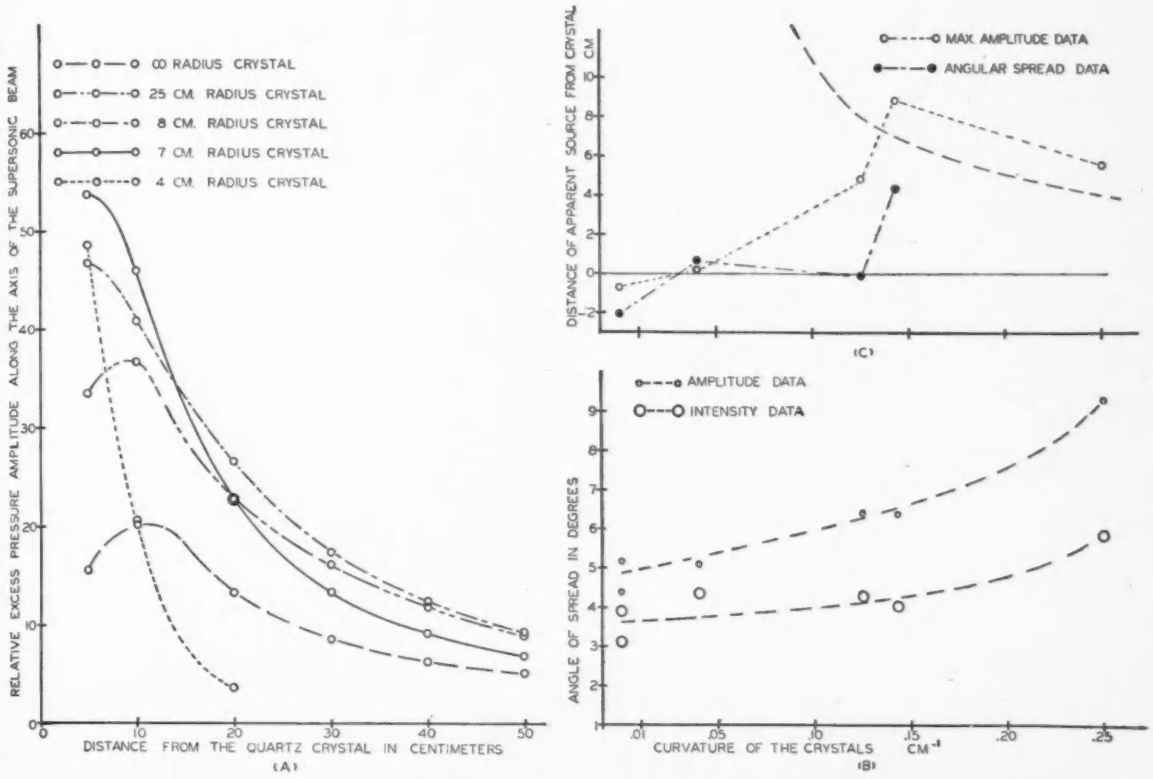
∞ RADIUS CRYSTAL
25 CM. RADIUS CRYSTAL
8 CM. RADIUS CRYSTAL
7 CM. RADIUS CRYSTAL
4 CM. RADIUS CRYSTAL
RELATIVE EXCESS PRESSURE AMPLITUDE ALONG THE AXIS OF THE SUPERSONIC BEAM
DISTANCE FROM THE QUARTZ CRYSTAL IN CENTIMETERS
(A)
MAX. AMPLITUDE DATA
ANGULAR SPREAD DATA
DISTANCE OF APPARENT SOURCE FROM CRYSTAL IN CM.
(C)
AMPLITUDE DATA
INTENSITY DATA
ANGLE OF SPREAD IN DEGREES
CURVATURE OF THE CRYSTALS CM⁻¹
(B)

FIG. 6A. The relative excess pressure amplitude along the axis of the beam generated by the five crystals from data similar to that in Fig. 4. B. The angle of spread of the beam half-width as a function of crystal curvature from the data in Fig. 3 and Fig. 4. C. The apparent point source of the supersonic beam as a function of the crystal curvature from the data in Fig. 3 and Fig. 4 found by computing (1) the position of the vertex of the angle of spread, and (2) the point from which the amplitude along the beam axis decreases as the distance.

square of the distance along the axis of the supersonic beam.[4] These results which give additional information about the relative focusing action of the crystals are plotted in Fig. 6C. The dashed line at the upper right of the graph is the locus of the radius of curvature. There was not enough information obtained for the 4-cm radius crystal to make a reliable calculation of the vertex position from the angular spread data. The trends of both types of analyses are the same. The 7- and 4-cm radius crystals have a focus near their radius of curvature as shown by Fig. 6A and Fig. 6C agreeing roughly with Greutzmacher's results. Although his crystals were larger, the ratio of the crystal diameter to the wave-length in water produced by the crystal is comparable to that for the 4-cm radius used here.

Figure 6A gives information at 1110 kilocycles which is rather far from the resonance frequencies of the crystals. If these results are combined with a knowledge of the crystal behavior as a function of frequency at some distance from the generator, the data become more useful. Figure 7 represents the excess pressure amplitude at 30 cm from the generator on the beam axis as a function of exciting frequency when the voltage is kept constant at the value used for the data in Fig. 6A. The points on the graph in Fig. 6A at 30 cm are the intersections of the curves in Fig. 7 with the dotted ordinates at 1110 kilocycles. One can now find rough values for the excess pressure amplitude at any distance from each of the four small curvature crystals at any frequency within the range shown, by extrapolation from Fig. 6A and Fig. 7. The results of this process are summarized in Table I which gives the relative excess pressure amplitude at the frequency of maximum response for each crystal. This table predicts that the

[4] G. W. Stewart and R. B. Lindsay, *Acoustics* (D. Van Nostrand Company, Inc., New York, 1930), p. 253.

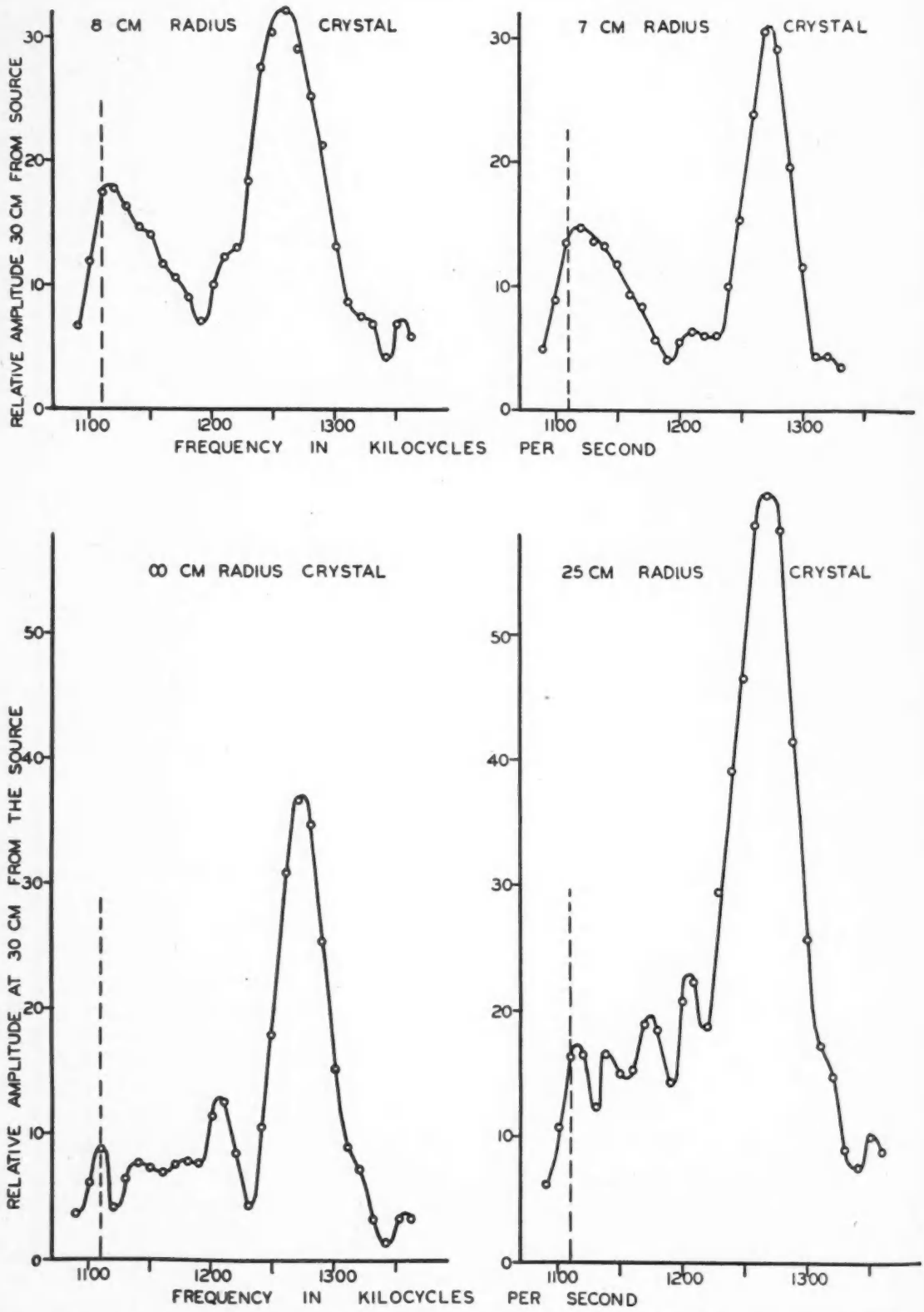

FIG. 7. The relative excess pressure amplitude on the axis of the beam at 30 cm from the generator as a function of the frequency with the crystals concave toward the water excited by a constant signal of 150 volts.

TABLE I. The relative excess pressure amplitude for maximum response from the crystals at several distances from the generator.

Distance from generator (cm)	Relative excess pressure amplitude			
	cm crystal ν=1272 kc	25-cm crystal ν=1268 kc	8-cm crystal ν=1260 kc	7-cm crystal ν=1272 kc
5	70.6	127.1	89.3	128.4
10	85.6	139.0	78.8	115.2
20	56.9	86.4	48.9	52.6
30	36.7	61.4	32.1	30.9
40	26.9	45.1	22.8	21.2
50	21.8	35.8	17.1	14.9

25-cm radius crystal would give an amplitude equal to or larger than that from any other crystal studied at any distance from the crystal operated at resonance.

If one considers the axial amplitude *vs.* frequency curves taken at one distance from the generator as resonance curves for the crystals, information may be obtained concerning the shift of the resonance frequency for each crystal compared with that predicted from the thickness.[5] This, along with the frequency half widths of the resonance curves, is tabulated in Table II from the data plotted in Fig. 7.

The shift in the resonance frequency is within 2 percent for all the crystals and is not considered particularly significant. The lack of a continued broadening of the resonance curve with increased

[5] G. W. Stewart and R. B. Lindsay, *Acoustics* (D. Van Nostrand Company, Inc., New York, 1930), p. 257.

TABLE II. Comparison of the experimental resonance frequencies with those predicted from the crystal thicknesses.

Crystal radius (cm)	Maximum response frequency (kc)	Predicted frequency (kc)	Frequency shift (kc)	Half-width resonance curve (kc)
∞	1272	1255	17	50
25	1268	1255	13	65
8	1260	1255	5	69
7	1272	1269	3	48

crystal curvature which one might expect from consideration of the increased reaction on the crystal by the water may have its basis in the supposition that it is more difficult to excite mechanical vibrations in a greatly curved crystal, except near the resonance frequency, because of the mechanical constraints introduced within the crystal itself.

An examination of all the data presented here seems to foster the conclusion that a slightly curved crystal gives a greater output close to the generator as well as at a large distance away than one of zero curvature, but that this advantage is owing primarily to increased amplitude of vibration for a given impressed voltage rather than to a confinement of the output energy within a smaller solid angle. This could be of importance in getting larger supersonic intensities with a given crystal cut than is at present possible using a flat crystal with the practical limitations on the voltage which may be applied to the quartz plate.

Notes on Distortion in Phonograph Reproduction Caused by Needle Wear

B. B. BAUER
Shure Brothers, Chicago, Illinois
(Received February 2, 1945)

1. INTRODUCTION

IN practically all theoretical work dealing with disk reproduction it has been assumed that the play-back needle has a spherical point. This assumption is usually correct when the needle is new. But the needle point does not long remain spherical. After some use, the needle develops "flat" spots at the points of contact with the groove. Such a needle can no longer faithfully follow the groove modulation, giving rise to loss in high frequency output and to distortion. Questions have frequently arisen as to the amount of wear which may be tolerated before the needle is discarded.

During the steel-needle era, the problem was simply disposed of by replacing the needle after each play of the record. The increase in popularity of the so-called "permanent point" needles in the late 30's brought about the need for a criterion of needle life. These notes were written in an attempt to fulfill this need. Precise analysis of the problem is extremely complex and some simplifying assumptions were made to hold the amount of labor down to a reasonable limit. The theory outlined has been found to be a valuable adjunct to experimental work dealing with the service life of phonograph needles under given requirements of fidelity of reproduction.

2. NEEDLE WEAR

Initially the needle point is generally spherical with a radius of 0.0025″ to 0.003″, although sphericity of the point and its radius varies considerably in different needles. The record groove is 0.006″ wide, trough-like in cross section with the side walls inclined at approximately 45° to the horizontal and a bottom radius of 0.002″ to 0.0025″. The initial cross section of needle (without load) and groove is shown in Fig. 1a.

When the needle is loaded with the weight of the pick-up, the spherical tip is pressed into the elastic groove walls and also, often, into the bottom of the groove. After a period of use, the needle is worn down to fit the groove. The wear is generally unequal on both sides because of the side-thrust existent in pivotally mounted tone arms.[1] The cross section of a needle which has been played a number of times is shown in Fig. 1b. As the needle is further used, wear continues to progress and eventually the needle point has a cross section as shown in Fig. 1c. The needle should be discarded long before it acquires such shape.

A good picture of the process which takes place may be obtained by observing the needle point as the wear progresses. Since the groove walls are elastic, the spherical needle point initially penetrates into the surface of a shellac record to the depth of approximately 0.0001″ under a pick-up force of 1 oz. This corresponds to a circular contact area of roughly 0.0014″ diameter. The initial cross section of the groove wall at the needle point is shown in Fig. 2. After the first few revolutions of the disk, the needle point shape remains practically unchanged, but there is considerable "scouring" or abrasion at the area of contact with the record. The abrasion is greatest at the portion which presses most deeply into the record, and this tends to even out the spherical surface. After a short period of use a fairly well-defined flat (or, more precisely, a singly curved surface) may be observed, which gradually blends into the spherical surface. The wear is most rapid at first and becomes more gradual as the unit pressure decreases due to the increased contact area. Because in a pivoted tone arm the angle between the needle and the groove is continuously changing, the flat actually exhibits a slight

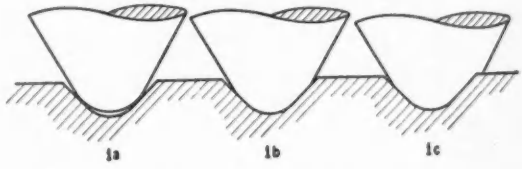

FIG. 1. Cross section of needle and groove in different stages of wear.

[1] B. B. Bauer, "Tracking angle in phonograph reproduction," Electronics **38**, No. 3 (March, 1945).

curvature. The approximate cross section of the flattened portion in the various stages of needle wear is shown by the dotted lines in Fig. 2.

The measurement of the size of the flat does not lend itself to a great deal of precision because there is no sharp line of demarcation between the generally flattened and the spherical portions. The method which we have found to be quite convenient consists of observing the needle tip under a medium power microscope (100× to 200×) while a distant source of light is directed perpendicularly to the flattened portion. The light is reflected from the almost singly curved surface as a straight line which can be measured by means of a calibrated eyepiece. This reflection is represented by the heavy line in Fig. 3, which shows the side view of a typical needle point with a 0.0025″ flat. In this manner the width of the flat can be determined with a precision of 0.0002″ to 0.0003″.

Needle wear varies enormously with the different factors involved. Common steel needles are admittedly useful for only a very limited number of plays. Much greater service time is obtained with rare-metal tipped needles. Sapphire-tipped needles provide a still further improvement. The wear is greater on shellac records than on nitrate records, and among the former it is substantially greater on the popularly priced records than on higher price disks. Pick-up force exerts a great deal of influence upon needle wear; indications are that wear increases with the needle force as a power considerably greater than unity. It is not the purpose of this study to present complete data on needle wear. For illustrative purposes, however, we show in Fig. 4 the size of the needle flat developed in three needles of different types as a function of the playing time. One-oz. pick-ups and popularly priced 10″-commercial shellac records were used. It should be carefully noted that these results are neither average nor representative of a given class of needles, for there are great variations within a class because of the use of different alloys, jewels, etc. Our observations suggest, however, that they are fairly typical of what one may expect under the conditions stated. It is seen that a substantial amount of wear takes place after a limited period of playing time, even on the so-called "permanent point" needles. It becomes of importance therefore to ascertain when a needle should be discarded if given fidelity requirements are to be met.

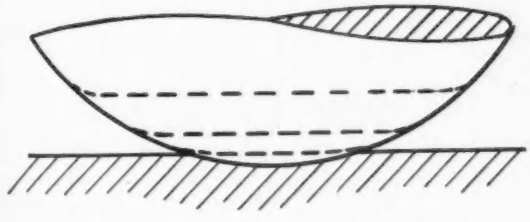

FIG. 2. Initial cross section of groove and needle loaded with a 1-oz. pick-up.

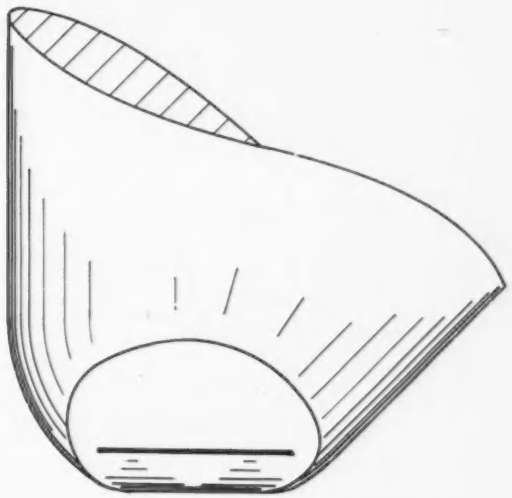

FIG. 3. Side view of worn needle.

3. ANALYSIS OF DISTORTION

Figure 5 shows the groove and needle in cross section at the two extreme positions of modulation, M and N. The groove modulation is usually thought of as consisting of horizontal (or vertical) translation of the groove cross section. For the purpose of analysis, we are following a scheme similar to that employed by Pierce and Hunt,[2] and studying the motion imparted to the needle point by each groove wall separately, combining them later to obtain the complete equation of motion. For instance, the translation from M to N may be analyzed in the following manner: First, the plane containing the side wall J moves in the direction of the arrow j from J to J', the side wall K remaining stationary. This would

[2] J. A. Pierce and F. V. Hunt, J. Acous. Soc. Am. 10, 14 (1938).

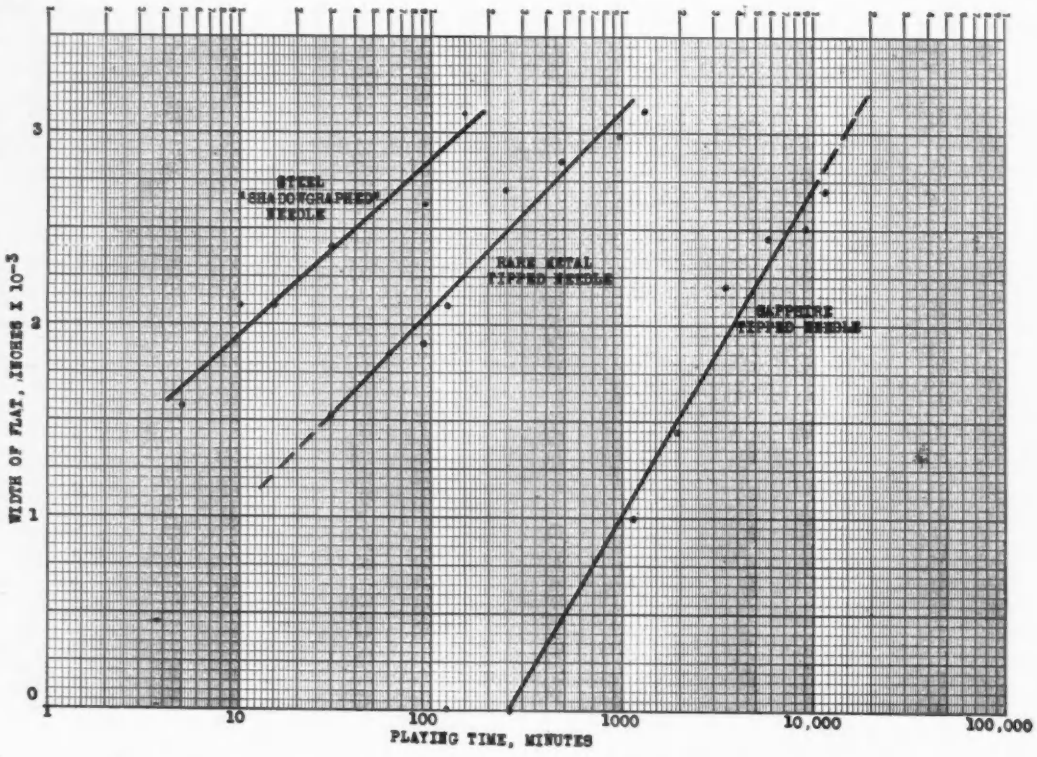

FIG. 4. Needle wear as a function of playing time measured on three different needles.

place the needle point in the imaginary position M'. Thence, the plane containing K moves to K', while J' remains stationary. The needle point slides now from M' to its final position N. Actually, of course, the two motions take place simultaneously and the needle point remains in a horizontal plane. A similar analysis may be employed in connection with hill-and-dale modulation. The total displacement of the needle point in a given direction is obtained by the algebraic addition of the projections of the needle motion owing to each side wall moving in the desired direction. This resolution of motion into the two components involves no approximations whatsoever since the groove walls are perpendicular to each other and the normal motion of one wall has no component in the direction of the normal motion of the other. The first step, therefore, in determining the behavior of a needle in the groove is the study of the action at a single side wall.

The equation of motion of the needle flat along a single side wall may now be determined as follows: In Figure 6, the flattened needle point is shown moving along a surface sinusoidally modulated in accordance with the equation

$$F(x) = a \cos 2\pi x/\lambda, \qquad (1)$$

where a is the amplitude, λ is the wave-length, and x is the distance measured in the direction of needle motion. It is assumed that the wall is

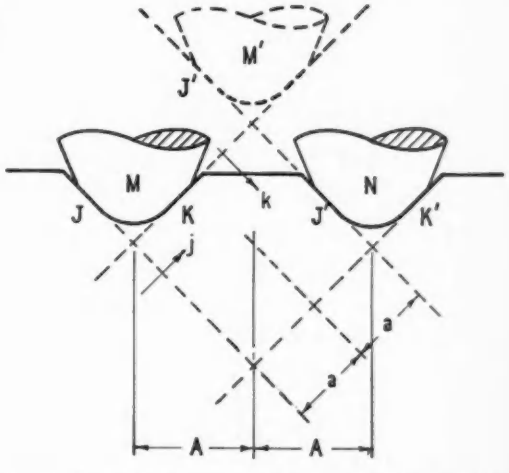

FIG. 5. Resolution of needle translation into motions perpendicular to the groove wall.

contacted by the flat portion of the needle only. (This would be obviously true only for low values of modulation. For large values of modulation both the flat and the spherical portion come into contact with the groove during the cycle and the situation becomes a good deal more complex.) Assuming that there is no deformation of the groove material, the center point of the flat executes the following motion:

$$f(x)=a\cos(2\pi/\lambda)(x+c)\cdots(-\lambda/2<x<-c)$$
$$a\qquad\qquad\cdots(-c<x<+c)$$
$$a\cos(2\pi/\lambda)(x-c)\cdots(c<x<\lambda/2), \qquad (2)$$

where c is $\frac{1}{2}$ the flat width d. This motion may be analyzed into its harmonic components by substitution into the Fourier series formulae. The resulting equation has the form:

$$f(x)=a_0+a_1\cos(2\pi x/\lambda)+a_2\cos 2(2\pi x/\lambda)+\cdots a_n\cos n(2\pi x/\lambda), \qquad (3)$$

a_0 is of no interest in this study (although it might be of interest in a study of needle tracking) as it denotes a constant displacement. The other coefficients are given by the equation:

$$a_n=a\left\{\left(\cos\frac{2\pi c}{\lambda}\right)\left(\frac{\sin\pi(1-n)}{\pi(1-n)}+\frac{\sin\pi(1+n)}{\pi(1+n)}-\frac{\sin(2\pi c/\lambda)(1-n)}{\pi(1-n)}-\frac{\sin(2\pi c/\lambda)(1+n)}{\pi(1+n)}\right)+\left(\sin\frac{2\pi c}{\lambda}\right)\left(-\frac{\cos\pi(1-n)}{\pi(1-n)}-\frac{\cos\pi(1+n)}{\pi(1+n)}+\frac{\cos(2\pi c/\lambda)(1-n)}{\pi(1-n)}+\frac{\cos(2\pi c/\lambda)(1+n)}{\pi(1+n)}\right)+\frac{2}{\pi n}\sin n\frac{2\pi c}{\lambda}\right\}. \qquad (4)$$

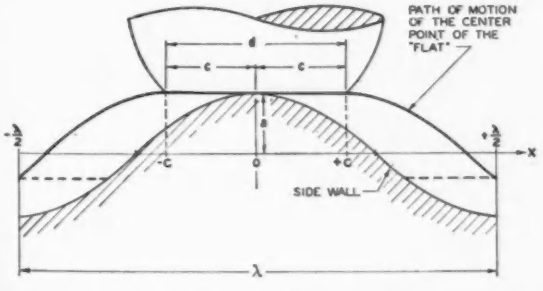

FIG. 6. Analysis of distortion because of needle flat.

It is interesting to observe that the quantity in brackets is independent of amplitude a. Therefore, distortion caused by needle wear (within the limits of validity of the assumptions made) is independent of amplitude, and is apt to be

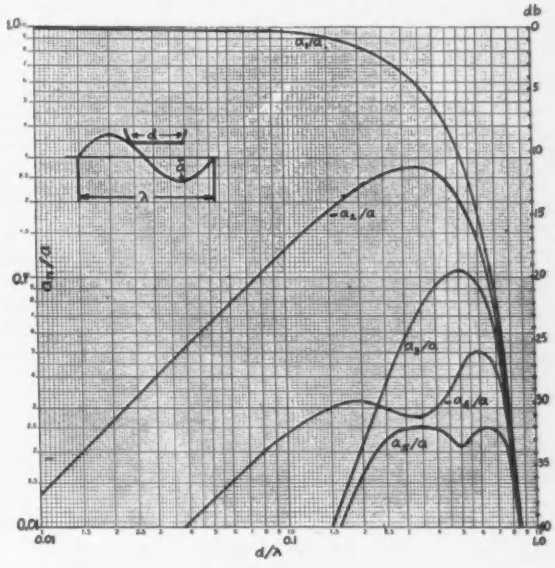

FIG. 7. Fourier coefficients for calculation of needle wear distortion.

equally prevalent during the piano and the forte passages. This is unlike tracing[2] and tracking[1] distortions which increase in severity with the amplitude of the groove modulation. Because of the curvature of the flats, Eq. (4) appears to be subject to better experimental verification at large rather than at small values of modulation.

Graphs of a_n/a as a function of d/λ are given in Fig. 7 for harmonics up to the fifth. For convenience, the decibel scale is included at the right. Distortion in percent may be obtained by dividing a_n/a by the a_1/a corresponding to any given d/λ. This is in terms of amplitude. However, most play-back systems are adjusted to operate at a constant velocity characteristic in the frequency range above 300 to 500 c.p.s. In velocity-type systems each component should be multiplied by its harmonic number. It is seen, therefore, that distortion attains very large values before there is a substantial reduction in the output level of the fundamental component. This contradicts the common belief that the principal effect of needle wear is a loss in high frequency response.

In the above analysis, single-tone distortion only has been considered. In dealing with complex tones, intermodulation products arise causing severe disturbance. It is to be hoped that this phase of the subject can be given attention at some future date.

4. HILL-AND-DALE MODULATION

Let the vertical translation of a hill-and-dale modulated groove be given by the equation $A\cos(2\pi x/\lambda)$. Then the normal component of motion of each side wall is given by the equation $a\cos(2\pi x/\lambda)$ where $a=A/\sqrt{2}$.

Assume that at the side wall J (Fig. 5) the needle point executes a motion, in the direction normal to J, given by Eq. (3). Rewriting in terms of a_n/a, and leaving out a_0 (which is of no interest here), the motion owing to J is given by:

$$j_v(x)=a\left(\frac{a_1}{a}\cos\frac{2\pi x}{\lambda}+\frac{a_2}{a}\cos 2\frac{2\pi x}{\lambda}+\frac{a_3}{a}\cos 3\frac{2\pi x}{\lambda}\cdots\right), \quad (5)$$

and the normal motion owing to K is given by

$$k_v(x)=a\left(\frac{a_1'}{a}\cos\frac{2\pi x}{\lambda}+\frac{a_2'}{a}\cos 2\frac{2\pi x}{\lambda}+\frac{a_3'}{a}\cos 3\frac{2\pi x}{\lambda}\cdots\right). \quad (6)$$

In Eq. (6) the a''s are used because the flats at both side walls may be of different dimensions, and hence, in general, $a_n'/a\neq a_n/a$. The vertical components of motions at J and K are found by dividing Eqs. (5) and (6) by $\sqrt{2}$. To obtain total vertical displacement of the needle point the two vertical components are added; when this is done and $a=A/\sqrt{2}$ is substituted, the equation of vertical displacement $V(x)$ is obtained:

$$V(x)=A\left\{\frac{1}{2}\left(\frac{a_1}{a}+\frac{a_1'}{a}\right)\cos\frac{2\pi x}{\lambda}+\frac{1}{2}\left(\frac{a_2}{a}+\frac{a_2'}{a}\right)\cos 2\frac{2\pi x}{\lambda}+\frac{1}{2}\left(\frac{a_3}{a}+\frac{a_3'}{a}\right)\cos 3\frac{2\pi x}{\lambda}\cdots\right\}. \quad (7)$$

If the two needle flats are equal, $a_n'=a_n$ and Eq. (7) reduced to:

$$v(x)=A\left\{\frac{a_1}{a}\cos\frac{2\pi x}{\lambda}+\frac{a_2}{a}\cos 2\frac{2\pi x}{\lambda}+\frac{a_3}{a}\cos 3\frac{2\pi x}{\lambda}\cdots\right\}. \quad (8)$$

The coefficients of the fundamental tone and of the harmonics can be obtained directly from Fig. 7. The distortion which attains in a hill-and-dale system of recording because of needle wear is, therefore, of the same nature as that which occurs at a single side wall.

5. LATERAL MODULATION

Let the lateral translation of a modulated groove be given by the equation $A\cos(2\pi x/\lambda)$. Then the normal component of motion of the side wall J is given by the equation $a\cos(2\pi x/\lambda)$ where $a=A/\sqrt{2}$. The motion of side wall K is reversed from that at J and 180° out of phase and is therefore given by the equation

$$-a\cos\left(\frac{2\pi x}{\lambda}+\pi\right).$$

Following the same procedure as that in Section 4, the motion in the direction normal to J is given by

$$j_L(x)=a\left\{\frac{a_1}{a}\cos\frac{2\pi x}{\lambda}+\frac{a_2}{a}\cos 2\frac{2\pi x}{\lambda}+\frac{a_3}{a}\cos 3\frac{2\pi x}{\lambda}\cdots\right\},$$

and the motion normal to K is given by

$$\begin{aligned}k_L(x)&=-a\left[\frac{a_1'}{a}\cos\left(\frac{2\pi x}{\lambda}+\pi\right)+\frac{a_2'}{a}\cos 2\left(\frac{2\pi x}{\lambda}+\pi\right)+\frac{a_3'}{a}\cos 3\left(\frac{2\pi x}{\lambda}+\pi\right)\cdots\right]\\&=a\left(\frac{a_1'}{a}\cos\frac{2\pi x}{\lambda}-\frac{a_2'}{a}\cos 2\frac{2\pi x}{\lambda}+\frac{a_3'}{a}\cos 3\frac{2\pi x}{\lambda}\cdots\right). \quad (9)\end{aligned}$$

The horizontal components of motion at J and K are found by dividing Eqs. (8) and (9) by $\sqrt{2}$. To obtain total horizontal displacement of the needle point, the two horizontal components are added; when this is done and $a=A/\sqrt{2}$ is substituted, the equation of total horizontal displacement $H(x)$ follows:

$$H(x)=A\left\{\frac{1}{2}\left(\frac{a_1}{a}+\frac{a_1'}{a}\right)\cos\frac{2\pi x}{\lambda}+\frac{1}{2}\left(\frac{a_2}{a}-\frac{a_2'}{a}\right)\cos 2\frac{2\pi x}{\lambda}+\frac{1}{2}\left(\frac{a_3}{a}+\frac{a_3'}{a}\right)\cos 3\frac{2\pi x}{\lambda}\cdots\right\}. \quad (10)$$

If the two needle flats are equal, $a_n=a_n'$ and Eq. (10) reduces to:

$$h(x)=A\left(\frac{a_1}{a}\cos\frac{2\pi x}{\lambda}+\frac{a_3}{a}\cos 3\frac{2\pi x}{\lambda}\cdots\right). \quad (11)$$

The coefficients of the fundamental and of the harmonics can be obtained directly from Fig. 7. It is seen, therefore, that distortion which attains in a lateral system of recording because of needle wear is similar to that which occurs at a single side wall, except that even harmonics tend to cancel out. This cancellation is not perfect unless the two needle flats are exactly alike.

6. DISCUSSION

We have attempted to formulate a tentative relation which might be used in determining the service life of phonograph needles in lateral disk reproduction. We are proposing it with considerable hesitation because we expect the manufacturers of needles to maintain that it is too strict, and the purists from the various scientific groups to claim that it is too lax. The chance is probably well worth taking, for the comments resulting therefrom cannot avoid having a beneficial result upon the art. We are proposing that maximum needle life be predicated upon a flat size not in excess of $\frac{1}{2}$ the wave-length at the inner grooves of the highest frequency to be reproduced. There is some question as to what constitutes the "highest frequency . . ." and therefore we have arbitrarily assumed at that frequency the system output is 10 db below the average 300–3000 c.p.s. level. Formulated in algebraic terms,

$$d_{\max}=\lambda_{\min}/2=\frac{\pi r_{\min}(\text{r.p.m.})}{60F_{\max}}, \quad (12)$$

where $d_{\max}$ is the maximum permissible size of flat, inches, $r_{\min}$ is the inner radius of the record, $F_{\max}$ is the effective upper frequency of the system, and $\lambda_{\min}$ is the least wave-length to be reproduced. It is interesting to observe some of the implications of the above formula. Assume a velocity-type reproducing system to have an upper frequency range of 5 kc. Let d/λ at the inner radius be 0.1 at 1000 c.p.s. Inasmuch as the even harmonics are cancelled (or very nearly so) only the odd harmonics are considered. From Fig. 7, and in terms of the amplitude of groove modulation, the fundamental is found to be 0.96 and the third harmonic is negligible. At 1700 c.p.s., d/λ is 0.17, the fundamental output drops to 0.88 and the third harmonic is 0.014, which constitutes 1.6 percent based upon amplitude-type modulation and 4.8 percent based upon velocity-type modulation. The third harmonic frequency is 5100 c.p.s. or just beyond the upper frequency limit. Harmonic components above 1700 c.p.s. increase greatly in magnitude but they are outside of the upper frequency range of the system. Therefore, if $d/\lambda_{\min}$ is not allowed to exceed $\frac{1}{2}$, one might be tempted to assume that maximum distortion at any one frequency will not exceed 4.8 percent, and perhaps judge our formula as overly strict. However, it must not be forgotten that when complex sounds are reproduced, distortions occurring at high frequency give rise to intermodulation components which are within the frequency range of the system, and which have a very great nuisance value.[3] In addition, when d/λ approaches $\frac{1}{2}$ there is a significant drop in output. For instance, in the system under consideration the 5000 c.p.s. ($d/\lambda=\frac{1}{2}$) output is down to 0.34 of the recorded amplitude, which constitutes a loss of 10 db. Also distortions at this frequency are very substantial. We should, therefore, feel extremely uneasy in employing a needle in which the flat

[3] J. K. Hilliard, "Distortion tests by intermodulation method," Proc. I. R. E. **29**, No. 12 (December, 1941).

had reached dimensions greater than those expressed by Eq. (12).

This brings us to the question of what one may expect in the way of service life from a phonograph needle. If one is in possession of data such as are given in Fig. 4, this question can now be easily answered. For system fidelity which we have arbitrarily rated in terms of high frequency cut-off as Low (3 kc), Medium (4 kc), Good (5 kc), and Excellent (8 kc), and assuming an inner radius of $2\frac{1}{4}''$ as being quite common; Table I was drawn up for the three needles used in the tests of Fig. 4. While the records employed in our tests were of the type which does not lend itself to reproduction of frequencies beyond 5 kc because of attendant surface noise, the 8-kc life is given in order to show that a limited amount of use on popular price records may impair the value of a needle (or a pick-up with a permanent point needle) for high fidelity reproduction on better-class surface disks.

Information given in connection with the sale of the "permanent-type" needles leads the user to expect a life substantially greater than that shown in Table I, which, it must be remembered, is based upon 1-oz. needle force and not the 2–$2\frac{1}{2}$ oz. force commonly found in pre-war home phonographs. It becomes apparent that the various claims for long life made by the manufacturers of "permanent-point" needles have not been based upon careful investigation. However, not all of the blame rests with the manufacturers for there has been little attention given by the scientific groups to the fact that the "permanent points" do wear, and no previous attempts have been made, to our knowledge, to establish standards for needle wear. The needle life ratings given by the manufacturers have, therefore, been based upon competitive pressure; rather than upon a standardized set of measurements.

In the reproduction of hill-and-dale recording with a worn needle one may expect a substantially larger amount of distortion than in lateral recording, because there is no cancellation of the even harmonics, and because it is not feasible to compensate for this fact by re-recording with phase inversion as is done to diminish tracing distortion. This factor may have had some bearing upon the disappearance of hill-and-dale (Edison-type) disks used in some of the old mechanical phonographs. The problem is probably not extremely significant with broadcast transcriptions which, because of the lack of abrasive filler, are less hard on needles than are shellac pressings. This fact should be considered, however, in connection with recent proposals to introduce broadcast-type hill-and-dale records into the home field, and in which one dual-type pick-up might be called upon to play both the lateral shellac records and the hill-and-dale broadcast-type records.

TABLE I. Recommended maximum number of plays (3 min./play) with various needles tested using 10″ 78 r.p.m. shellac records and 1-oz. pick-up. (Based upon $d_{max}=\lambda_{min}/2$; $r_{min}=2\frac{1}{4}$ inches.)

System fidelity	Upper frequency cut-off	Maximum "flat" d inches	Max. No. of plays with needle tested: "Shadow-graphed" steel	Rare metal tipped**	Sapphire tipped
Low	3 kc	0.0031	62	330	5700*
Medium	4 kc	0.0023	8	60	2000
Good	5 kc	0.0018	2	20	1000
Excellent	8 kc	0.0012	—	5*	440
			(Records used unsuitable for excellent fidelity because of surface noise)		

* Readings extrapolated.
** It is thought that these values are somewhat lower than usual because of lowered amounts of osmium because of war scarcity.

7. EXPERIMENTAL VERIFICATION

Almost everyone who has performed work of this character is acquainted with the fact that experimental measurements are wrought with many difficulties. One has to contend with the lack of suitable records, with variations of turntable speed and with all sorts of effects connected with the elasticity of the record and stylus material, differences in the cross section of record grooves, peculiarities of the cutting head and of the process of record duplication, etc.

Distortions are most severe at the inner grooves and at high frequencies. Manufacturers of records have avoided placing high frequencies at the inside of test records. The only test record which we found suitable for distortion measurements was the "Audiotone." λ at the inner 1000 cycle band is 0.0184″. In one of these distortion measurements, a sapphire-tipped needle had a 0.003″ flat on one side and a 0.0033″ flat on the other side. The values of d/λ for the above condition were 0.163 and 0.179, respectively. The corresponding Fourier coefficients taken from

Fig. 7 are:

$$a_1/a=0.89, \quad a_2/a=-0.195, \quad a_3/a=0.0127,$$
$$a_1'/a=0.87, \quad a_2'/a=-0.210, \quad a_3'/a=0.0156.$$

Entering the above into Eq. (10), and multiplying each coefficient by its harmonic number in order to take care of velocity-type pick-up characteristic, the following equation results:

$$H(x)=A(0.88\cos\theta)+0.022\cos 2\theta + 0.0423\cos 3\theta\cdots \quad (13)$$

where $\theta=2\pi x/\lambda$. Harmonic distortion, in percent, is percent second $=(0.022/0.88)\times 100=2.5$ and percent third $=(0.0423/0.88)\times 100=4.8$ percent. Actual measurements of distortion showed 3.5 percent second harmonic and 5.0 percent third harmonic content. When played with a spherical point needle, second harmonic distortion was 0.8 percent and third harmonic distortion was 2.0 percent which are, in part, explainable by the theory of tracing distortion given by Pierce and Hunt.[2] Distortions at the outer 1000-c.p.s. grooves, with both needles, were well below 1 percent.

The above calculations were carried out in some detail in order to provide an example of the use of Fig. 7 in estimating distortion. The loss in fundamental output is simply given by the coefficient of the fundamental term in Eq. (10). In performing experimental work for high frequency loss, the only convenient (but not too satisfactory) pressing found was the Columbia Test Record number 10003-M. Care had to be exercised to keep the "flats" in alignment with the groove. Agreement was generally good up to 4 kc and reasonably good up to 6 kc. Difficulties were encountered at frequencies above 6 kc as the readings appeared to vary greatly with positioning of the needle. When nitrate disks are used, agreement is less good indicating yielding of the record material.

During the process of obtaining the data of Fig. 4, we had occasion to compare on an "A–B" basis the quality of reproduction of the test needle against that of a similar control needle. In each instance, distortion and loss of highs were quite perceptible at the inner grooves when size of the flat had reached or exceeded the maximum dimension given by Eq. (12). This afforded a rough confirmation of the theory. We mention these facts without claiming ultimate verification, inasmuch as considerably more experimental work is required than we had been able to schedule at this time.

8. CONCLUSION

Precise determination of distortion caused by needle wear is a difficult matter because of the many variables which are involved. We hope that these notes will shed some light on the subject and promote further discussion and study.

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Singing Flames

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The flames considered are those which maintain vibration of the air in a surrounding "air tube." Earlier theories are reviewed. Rayleigh's theory involves standing waves in the gas supply tube and leads to certain lengths of gas tube for which singing does not occur. It is now found that maintenance of vibration in the air tube may be excellent when the gas tube is so long that no appreciable standing waves are formed in it, and that under suitable conditions there are no lengths of gas tube for which a flame will not sing. Rayleigh's theory is modified by taking into account (1) the increase in viscosity which the flame brings about in the orifice from which it burns and (2) the progressive waves that run downward through the gas tube. These waves involve a maximum rate of efflux of gas near the phase of least pressure in the air tube, whereas Rayleigh's theory involves a maximum rate of efflux a quarter of a period earlier or later, depending on the length of the gas tube. If the most rapid efflux is near the phase of least pressure, and if the flame gases rise from the orifice to the top of the flame in approximately half a period, maintenance is possible. In thirteen cases where the flame sang, values obtained for the time of rise run from $0.6T$ to $0.9T$; and in sixteen cases where the flame was silent, they run from $1.2T$ to $3.3T$. In view of approximations made in reaching these results they are regarded as satisfactory. When the gas tube is of only moderate length, standing waves in it may be superposed on the running waves. This superposition leads to the possibility of lengths of gas tube for which the flame will not sing. Regions of silence are more likely to occur when the flame is small. The size of the flame is also a factor in determining the distance to which it must be inserted in the air tube before maintenance is possible. The distance is a minimum for flames of moderate size. The amended theory gives explanations of these facts and of several others. The initiation of the vibration is attributed to the slight disturbances that are always present in the atmosphere.

INTRODUCTION

ABOUT ten years after the discovery of hydrogen, Higgins[1] heard a musical tone from what may have been the first singing flame. He was demonstrating that the burning of hydrogen produces water, and to show this he lowered over the flame a vertical glass tube, closed at the upper end. The singing that ensued has aroused the interest of many investigators. In most cases the flame burns at a rather small orifice, which is inside a larger vertical tube. Following Richardson,[2] I shall use the term "gas tube" for the tube through which the gas comes to the orifice at which it burns, and the term "air tube" for the larger tube around it.

Various facts have been learned about these singing flames, but no satisfactory explanation of their action has yet been given. The present paper summarizes a number of the hypotheses that have been suggested, cites some new facts, and proposes an explanation that seems to fit a larger proportion of the facts than any that have heretofore been given.

Some well-substantiated facts about these flames are the following:

(1) The vibration is that of the air in the air tube, and not that of the walls of the tube. The pitch is approximately that to be expected from the contained air.

(2) Singing may be obtained from the burning of other gases instead of hydrogen.

(3) Some combinations of burner, gas, and air tube will sing, and others will not. The orifice at which the gas burns is usually from half a millimeter to a millimeter or two in diameter.

(4) A flame that is silent may sometimes be set singing by some other sound.

(5) While the flame is singing it grows larger and smaller with the frequency of the tone that it gives. If the vibration becomes too violent, the flame may actually be extinguished.

VARIOUS HYPOTHESES

The earliest explanations of the singing were neither very clear nor very convincing. De Luc[3] and Hermbstädt[4] found the explanation in a

[1] Bryan Higgins, Nicholson's J. **1**, 130 (1802). Higgins observed the effect in 1777.

[2] E. G. Richardson, Proc. Phys. Soc. London **35**, 47 (1922–23).

[3] J. A. De Luc, *Idées sur la Météorologie* (1786), Vol. 1, p. 171.

[4] Hermbstädt, *Crell's Chemische Annalen* (1793), Part 1, p. 355.

rapid formation of water vapor, and then a sudden condensation of it. Delarive[5] proposed a cooling of the water vapor by contact with the air, with a consequent contraction that permitted fresh air to press closer to the flame and so form more water vapor. Nicolson[6] thought that there might be alternately too much fuel and then too much oxygen from the surrounding air.

Faraday[7] obtained singing under circumstances where there could be no condensation of water vapor. He did this with a tube too hot for the condensation of water vapor, and also when the gas that burned was carbon monoxide. He suggested that the air mingles with the inflammable material and thus forms "exploding mixtures, which are fired by the contiguous burning parts. . . . The detonations taking place more rapidly and regularly [than in a roaring flame], and in smaller quantities, the sound becomes continuous and musical, and is rendered still more so by the effect of the tube in forming an echo." Tyndall[8] regarded these explosions as "undoubtedly the true source of the sounds"; and a series of explosions is involved in explanations proposed by Zoch[9] and by Rogers.[10] The explanation given by Rogers was based in part on the work of Masson,[11] who had studied the sounds produced by a stream of water from a small orifice. Rogers supposed that in a singing tube there is a similar vibration of the gas at the orifice, and that this vibration leads to explosions which are reinforced by the air tube.

Several experimenters,[12–14] however, found that in each cycle the flame may burn alternately above the orifice and down inside it, but probably is never extinguished and rekindled, in the way that Faraday is usually thought to have had in mind. Apparently the maintenance is not by a series of explosions.

A number of investigators[9, 15–17] have proposed explanations that depend on the draft set up in the air tube. The earliest, and perhaps the clearest, of these explanations was that given by Schrötter,[15] who assumed that the gas which burns is hydrogen, and that it burns above the vessel in which it is generated. Schrötter pointed out that the draft in the air tube involves a decrease in pressure, which in turn leads to a greater rate of efflux of the gas and a larger flame. Since the rate of production of hydrogen is not proportionately increased, there is a diminution of pressure in the generating flask, followed by a decrease in the rate of efflux. This decrease would be only to the original rate of efflux if it were not that the decreasing size of the flame entails a motion of the surrounding air toward the orifice, and the inertia of the air carries it beyond equilibrium and drives the flame down into the top of the gas tube. Since the products of combustion, after they have cooled, have a smaller volume than before the burning occurred—I think this is his meaning—their decrease in volume causes a decrease in the pressure in the upper part of the gas tube, so that gas from the generator rises again more rapidly, and this rise is aided by the upward draft in the air tube. Thus the flame rises and falls periodically, and the rising and falling flame maintains the vibration of the air in the air tube in much the same way that a tuning fork would maintain it.

Another hypothesis which also depends on the draft in the air tube, but is very different from Schrötter's, was proposed by Foch.[17] He assumes that the velocity of the draft is close to the critical velocity at which turbulence sets in. A slight increase in velocity leads to turbulence and a consequent reduction in velocity. The reduction in velocity restores streamline flow and a consequent increase in velocity. Thus the velocity becomes periodic, and vibration of the air in the air tube is maintained.

Foch supposed that there could be no maintenance when the tube is horizontal, and there is no through draft. But in the original experiment by

[5] Charles Gaspard Delarive, J. de Phys. **55**, 165 (1802).
[6] William Nicolson, Nicolson's J. **1**, 131 (1802).
[7] Michael Faraday, Quart. J. Sci. Arts **5**, 274 (1818).
[8] John Tyndall, Phil. Mag. **13**, 473 (1857).
[9] Ivan B. Zoch, Pogg. Ann. **127**, 580 (1866).
[10] William B. Rogers, Am. J. Sci. **26**, 1 (1858).
[11] A. Masson, Ann. Chim. Phys. **40**, 333 (1854); **41**, 176 (1854).
[12] J. Grailich and E. Weiss, Sitz. Wien. Akad., Math.-Phys. Classe **29**, 271 (1858).
[13] A. Töpler, Pogg. Ann. **128**, 126 (1866).
[14] H. V. Gill, Am. J. Sci. **4**, 177 (1897).
[15] A. Schrötter, Sitz. Wien. Akad., Math.-Naturwiss. Classe **24**, 18 (1857). Schrötter's observations were made in 1843, reported briefly in 1844, but not published more fully until this paper in 1857.
[16] A. Terquem, Pogg. Ann. **134**, 468 (1868).
[17] Foch, Comptes rendus **188**, 697 (1929).

Higgins[1] the air tube was closed at the top, a condition which would seem to prevent much draft, and both Sondhauss[18] and Rayleigh[19] have also succeeded in getting tubes to sing when closed at the top. Moreover, singing may occur when the air tube is horizontal,[12] and there is certainly no through draft. Dana[20] "found no difficulty in causing the flame to sing when inserted quietly into a horizontal tube, *carefully leveled*." (The italics are his). If the tube is too narrow the products of combustion collect and soon put the flame out, but "in a tube $1\frac{3}{4}$ inches in diameter and 3 feet long, the flame sang for an indefinite time." More recently Carrière[21] carried out a considerable study of singing flames with the air tube horizontal in order to avoid the effects of draft.

In view of these facts, any hypothesis which assumes that a draft is essential for the maintenance must be discarded. Although a draft is not essential, it does have some effect on the singing. With a horizontal air tube 4.5 cm in diameter and 83 cm long, I find that a small flame will sing for as long a time as I choose to listen, but it will not sing unless it is inserted to a distance of at least 20 cm. When the tube is raised to an angle of 45° the same flame will sing if it is brought in for 13 cm or more, and when the tube is vertical the flame need be brought only 11 cm into the tube. A draft through the air tube is not essential for singing, but does affect the maintenance in a minor way.

Gill[14] advanced a hypothesis in which he emphasized the fact that before the gas burns it is already under a pressure greater than atmospheric. Let the orifice of the gas tube be at a node in the air tube, and let there be already a slight vibration in the air tube. A rise of pressure in the air decreases the efflux of gas, thus reducing the size of the flame, whereas a drop of pressure in the air permits an efflux which is greater than if the air were not vibrating, and so increases the size of the flame. Thus, a larger flame "comes at such an instant, that it assists the expansion during the rarefaction." As a test of his hypothesis, Gill connected a manometric capsule to the gas tube and observed the singing flame and the manometric flame in a rotating mirror. The appearance in the mirror seemed to verify that the singing flame was largest when the pressure in the air tube was least. Nearly twenty years earlier Rayleigh[19] had reached a different conclusion. Gill did his work at Louvain, and he had apparently not seen Rayleigh's paper.

RAYLEIGH'S THEORY

The Theory

The theory that is best known was given by Lord Rayleigh.[19] He pointed out that in order to maintain a vibration in the air tube, the flame must supply heat more rapidly during a compression than during a rarefaction. If we suppose that the gas comes from the orifice most rapidly when the pressure in the neighboring air is least, and if we suppose further that the most heat is developed when the gas is coming out most rapidly, it is not difficult to see that the flame will damp any vibration that may exist in the air tube rather than increase and maintain it.

Rayleigh's explanation of the maintenance is based on an extensive series of observations by Sondhauss.[18] The gas tubes that Sondhauss used ended below in the flask in which the hydrogen was generated, or in another flask to which the hydrogen was led from a gasometer. He used a variety of lengths of gas tubes and a variety of lengths of air tubes. For a given gas tube he found that there were frequently at least two series of lengths of air tubes in which the flame would sing, separated by other lengths of air tubes in which he was not able to obtain singing. He also found that if a gas tube were partly plugged with a wick,[22] there was no singing when the top of wick was too far up in the gas tube. These facts led him to believe that a vibration in the gas tube is important.

[18] Carl F. J. Sondhauss, Pogg. Ann. **109**, 1, 426 (1860).

[19] Lord Rayleigh, Proc. Roy. Inst. **8**, 536 (1878); or *Theory of Sound* (The Macmillan Company, New York, 1896), Ed. 2, p. 226*ff*.

[20] James D. Dana, Am. J. Sci. **45**, 422 (1868).

[21] Z. Carrière, Rev. d'acoustique **4**, 149 (1935). Carrière restricts the term "singing flames" [*flammes chantantes*] to flames which sing of themselves, without any associated air tube or other resonator, and he uses the term "exciting flames" [*flammes excitatrices*] for the flames we usually call "singing flames," which maintain vibration in an air tube.

[22] In the literature this plug is sometimes referred to as if it were a wad of cotton batting. Sondhauss says that he used a cotton lamp wick—I suppose a round one—which he twisted in from below. Its position was often adjusted by means of two threads. By one thread it could be pulled upward, and by the other downward.

Rayleigh pointed out that when there is a vibration in the air tube, the pressure in the gas just before it emerges from the orifice must be practically in phase with that in the neighboring air. Thus a periodic change of pressure in the air tube sets up standing waves in the gas tube, and in these standing waves there is an antinode not far from the lower end of the gas tube. If the gas tube is shorter than quarter of a wave-length, the instant at which the particle velocity in the standing waves is greatest and directed upward toward the orifice comes a quarter of a period before the phase of maximum condensation. Allowing a short time for the burning, this provides the proper phase of heat supply, and maintenance by the flame is explained. If the length of the gas tube is greater than quarter of a wave-length and less than half a wave-length, similar reasoning shows that no maintenance is possible. For a greater length of gas tube another region of maintenance follows, and so on.

Rayleigh's theory certainly explains in a general way the observations that Sondhauss made. Sondhauss gave enough detail about the lengths of his tubes to make possible a quantitative test of Rayleigh's theory; but, so far as I know, no such study of Sondhauss's results has been published. From his Tables I and II I have made the necessary calculations. For the first region of singing it turns out that the length of his gas tube was in no case greater than about 0.2λ, and on Rayleigh's theory it should be less than 0.25λ. For the second region the lengths run from an average of about 0.35λ to 0.60λ, instead of from 0.5λ to 0.75λ; and for the third region from about 0.8λ to 1.1λ, instead of from 1.0λ to 1.25λ. There was doubtless some periodic change of pressure in the flask below the gas tube, and the lower end of the gas tube was not strictly at an antinode. Moreover, if Sondhauss's hydrogen was not pure[23] the wave-lengths were shorter than I have assumed, so that the numbers should be somewhat larger than those I have given. Thus Rayleigh's theory, involving standing waves in the gas tube, seems to fit rather well the results obtained by Sondhauss.

[23] Sondhauss says that he did not wait long enough for the hydrogen to become pure. The flask contained air before generation of the hydrogen began.

Rayleigh's Theory not Adequate

Richardson[2] carried out an experimental test of Rayleigh's theory, and his results seemed on the whole to support that theory. He did find, however, that the regions of singing are considerably wider than those admitted by Rayleigh's theory, and the same result was reached by Miss Porter.[24] Moreover, Zoch[9] says that a flame which burns completely, and has its zones sharply bounded, makes every air tube sing; and Gill[14] says that with a given gas tube he could obtain any pitch he desired by suitable adjustment of the size of the flame, its position in the air tube, and the length of the air tube.

Gill[14] obtained singing flames with ordinary coal gas, and found that he could take the gas directly from the house supply, without leading it first into a large flask or bottle. In the work that I am reporting, I, too, have used gas from a cock in the laboratory and have often led it directly to the orifice for the flame. With this arrangement it would seem that if standing waves, such as Rayleigh envisaged, are set up in the gas tube, there should be a node near the position of the partly closed gas cock,[25] so that, if Rayleigh's theory is correct, singing should occur for certain lengths of connecting tube, and not for others.

There are situations where this does not prove to be the case. Curve *a* in Fig. 1 shows, for different lengths of gas tube, the distance that a 5 cm flame had to be inserted in an air tube in order to obtain singing. Two points are to be noted: (1) It is true that the curve does give some indication of an effect which is periodic with changing length of gas tube. The period appears to be rather less than half a wave-length. (2) Although the length of gas tube changed by more than a wave-length, the flame sang well at every length that was tried. There were no regions of silence.

The gas outlet employed in this case was made of a short length of glass tubing with a bore of about 5 mm, drawn down to an orifice about 0.65

[24] Mildred Burnette Porter, M.A. thesis (1920), deposited in the library at Smith College, but not published.

[25] The adjustment needed in the gas cock to give flames that differed considerably in size was very slight. There was little effect on the size of the flame while the handle of the cock was turned through some 60° from the wide open position. Then in a degree or two the change was very marked.

mm in diameter, connected to the gas cock by pieces of glass and rubber tubing. The air tube was 99 cm long and had a bore of 3.4 cm. The wave-lengths were obtained by calculating the velocity of sound in the gas. A recent analysis of the gas was kindly supplied by the Northampton Gas Light Company, and the calculated velocity is about 1.25 times that of sound in air.

The results just mentioned suggest that standing waves in the gas tube may not be as important as Rayleigh supposed. Gill's manometric capsule, mentioned above, showed that the gas in the gas tube is certainly vibrating, as Sondhauss felt sure it was. Richardson[2] employed a similar external flame, which led to the same result. I have verified this periodic change in pressure in the gas tube by bringing the gas from the cock to a Y, and from the two sides of the Y to two flames, one in an air tube, the other burning in the open. A rotating mirror shows that the rising and falling of the singing flame in the air tube is accompanied by a similar rising and falling of the external flame.

But it does not necessarily follow that there are standing waves in the gas tube. With the singing flame connected to the gas cock through about seventeen meters of tubing, and the Y 560 cm back from the singing flame, the rising and falling of the external flame was still perfectly definite. With the Y 1170 cm back from the singing flame the rising and falling of the external flame was very small,[26] and with the Y at a distance of 1670 cm I no longer detected any change in the external flame. This test seems to show that in this last case, at least, no appreciable standing waves were set up in the gas tube. Yet the flame sang as well as ever.

In these tests the changing pressure near the flame sent progressive waves backward through the gas supply tube, and the tube was long enough to damp these waves very greatly. The rubber connecting tube was about 5.5 mm in inside diameter, and from a chart[27] showing the attenuation of sound waves in tubes of different sizes, I judge that in the last of the above cases

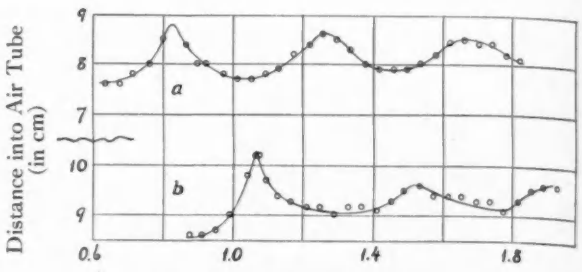


FIG. 1. Level to which a flame must be inserted into an air tube before singing is maintained. Curve *a* is for a 5.0-cm flame, with the gas tube connected directly to the gas cock. Curve *b* is for a 2.8-cm flame, with the gas tube ending below in an eight liter flask.

there must have been an attenuation of about 20 db as the waves traveled backward from the flame to the Y.

The vibrations of a singing flame may often be so vigorous as to extinguish the flame, and Richardson[2] came to the conclusion that the flame is most likely to be put out when the conditions are such that Rayleigh's theory indicates the possibility of singing. I have found that a flame which is blown out when connected to the gas cock through 180 cm of tubing is also blown out when the connecting tube has a length of seventeen meters—a length so great that any standing waves in the gas tube must have been very weak.

From these various facts it follows that the existence of standing waves in the gas tube is not essential to singing, and that Rayleigh's theory must either be abandoned or considerably modified.

A MODIFIED THEORY

Running Waves

In attempting to account for the maintenance, let us at first suppose that the gas tube is so long that no standing waves are formed in it, and let us suppose that some small vibration has been started in the air tube. Let us also assume that the changing pressure just inside the gas orifice is practically in phase with that just outside it. The changes in pressure are transmitted backward as running waves in the gas tube, and in these waves the particle velocity near the orifice is downward when the pressure is high, and upward when the pressure is low. Thus the gas

[26] Schaffgotsch, Pogg. Ann. **101**, 471 (1857), used a similar external flame, and found that he could still detect its vibration when it was 11.9 meters back from the singing flame.

[27] Harry F. Olson, *Elements of Acoustical Engineering* (D. Van Nostrand Company, Inc., New York, 1940), p. 98.

streams from the orifice most rapidly when the pressure in the air tube is low, and least rapidly when the pressure is high. This is a phase relationship which Rayleigh thought would be inimical to singing.

In the flame the gas is burning—downward at the top, inward at the sides. When the flame is steady, the upper margin of the region of combustion moves down through the gas at the same rate at which the gases move upward in space. If the gases are flowing upward more rapidly, the top of the flame is rising; and if they are flowing upward more slowly, it is falling. When the flame is not steady, the gases in the top of the flame move upward fastest when they are the gases that have come fastest from the orifice. If the rapidly ascending gases which come from the orifice when the pressure is low should rise to the upper part of the flame in the neighborhood of half a period of the vibration in the air tube, and if the flame gives out heat most rapidly when it is growing most rapidly, or shortly thereafter when it is largest, heat would be supplied most rapidly near the phase of maximum pressure, and the phase relationship would be conducive to maintenance. In any explanation of singing flames one important point to be taken into account must be the time in which the gases rise to the top of the flame.

Standing Waves

Turn next to cases where the lower end of the gas tube is in a vessel of considerable size. The gas in the gas tube has now a natural frequency of vibration, and standing waves in it are superposed on the running waves just considered. The resultant motion in the gas tube depends in part on the relative strengths of the two types of waves. If the frequency of the vibration in the air tube is close to a natural frequency of the gas in the gas tube, the standing waves forced in the latter are strong, and if the frequency in the air tube is far from any natural frequency of the gas tube, the standing waves are weak.

In the free vibration in the gas tube, we know that there is effectively an antinode just below the bottom of the tube and a node a short distance inside the top of the tube. The distance of the node below the top of the tube depends on the size of the orifice. If the orifice is much smaller than the bore of the tube, the node is near to the orifice, and in the fundamental mode of vibration the length of the tube is not far from a quarter of a wave-length.

In the forced vibration the length of the tube may, of course, bear an entirely different relation to the wave-length, and the orifice may be near to a node or far from it. When the orifice is close to a node the efflux arising from the standing waves is small, and there could be no maintenance of a vibration if running waves were not superposed on the standing waves. Whether singing occurs under these circumstances depends largely on the strength of the running waves.

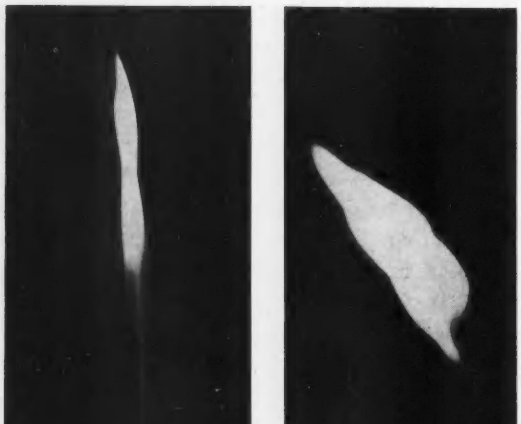
When the orifice is not very close to a node, the phase relationship between the velocity in the standing waves and that in the running waves depends on whether the orifice is nearer to a node in the gas tube or to an antinode. If there is a node a short distance below the orifice, the maximum rate of efflux in the standing waves occurs a quarter of a period before the minimum pressure in the air tube, so that in the neighborhood of the orifice the upward velocity in the standing waves is about a quarter of a period ahead of that in the running waves. If there is an antinode a short distance below the orifice, the maximum rate of efflux in the standing waves occurs half a period later, and the upward velocity in the standing waves is about a quarter of a period behind that in the running waves. So far as the standing waves are concerned, these relationships are those that were given by Rayleigh.

The superposition of standing waves on the running waves in the gas tube gives us, therefore, a maximum rate of efflux which comes (a) between three quarters of a period and half a period before the phase of maximum pressure in the air tube when the orifice is a short distance above a node, and (b) between half a period and quarter of a period before the maximum pressure when the orifice is a short distance above an antinode. Whether singing will occur in either case, or in both, is to be expected to depend on the time taken by the flame gases in rising to the top of the flame.

Viscosity in the Orifice

With an uninclosed flame, Barus[28] thought for a time that he had detected a pressure in

[28] Carl Barus, Science **60**, 137 (1924).



a *b*

FIG. 2. Two flames when near the end of a sounding organ pipe (see reference 31). In *a* the flame gases are rising more rapidly than in *b*. These photographs were kindly taken for me by Mrs. H. H. Hatheway, and I wish to express my hearty thanks to her.

the flame itself in excess of that outside it. He decided later that this pressure, which he observed in the supply tube below the flame, was probably caused by the increase in viscosity which the heat of the flame produced in the gas before it escaped from the orifice. Now various experimenters[2, 14, 18, 21, 24, 26, 29] on singing flames have found that the pressure in the gas tube is greater when the flame is singing than when it is silent. When the flame is singing, the top of the flame goes up and down, and the zone of most rapid combustion comes periodically closer to the orifice than when the flame is steady. So the orifice is heated more, the viscosity of the gas in it increases, the mean rate of efflux decreases, and the pressure below the flame increases. This increase in the viscous resistance in the orifice for a singing flame has apparently not been pointed out before, and, as will be shown later, it appears to aid in explaining a number of facts regarding singing flames.

TESTS OF THE THEORY

Upward Velocity in the Flame

How long does it take the gases to rise to the top of the flame? My first attempt to answer this question was made with a gas meter. Knowing the area of the orifice and the volume of gas that passed through the meter in a given time, it is easy to calculate the velocity of the gas as it comes from the orifice, providing that for this purpose it is permissible to regard the gas as incompressible. For several reasons this method cannot be expected to give very reliable values for the upward velocity in the flame, but the results were at least encouraging.

A better method was to have a flame burn freely near the open end of a horizontal organ pipe. The alternating velocity in the waves that come from the pipe wafts the flame back and forth as it rises, giving it a sinuous motion that has an envelope the lower part of which looks somewhat like one ventral segment of a vibrating string. A little analysis shows[30] that the time taken by the flame gases in rising to the constriction at the top of this ventral segment is a whole period of the organ pipe, rather than the half period we might at first suppose.

Photographs of two such flames are shown in Fig. 2.[31] The first constriction in flame *a* is about seven tenths of the way up the flame. In *b*, where the flame gases were rising more slowly, three constrictions are visible, and from their spacing it can be seen that there is a decrease in the upward velocity of the gases as they rise. For my purposes I have assumed that the upward velocity is constant, and that it is given by y/T, where y stands for the distance from the orifice up to the first constriction, and T for the period of the organ pipe.

On examining in front of the organ pipe flames of different heights from various orifices, I find that for a given orifice the distance y up to the first constriction is nearly proportional to the height H of the flame. y grows a little more slowly than in proportion to H, so that as H increases dy/dH decreases somewhat. I have, however, assumed that y is proportional to H,

[29] J. Würschmidt, Verh. d. D. Phys. Ges. **18**, 444 (1916).

[30] Ernst Mach, *Optisch-Akustische Versuche* (Calvé, 1873), p. 50.

[31] For each photograph the organ pipe was at the right. The deflection of the flame away from the pipe is explained by the fact that the flow of air when it swings outward from the pipe is not along the same line as when it swings inward. The inertia of the air carries it onward in the latter part of the outward swing, whereas on the inward swing there is a considerable curling in from the sides. The result is a wind that issues from the end of the pipe.

and I have found experimentally a value of y/H for each orifice.

With these assumptions, the frequency of the organ pipe, and the value for the ratio of y to H for each orifice, it is possible to obtain rough values for the upward velocity of the gases in silent flames of various sizes from various orifices. Then for an air tube of known frequency and a flame of known height, it becomes possible to calculate what fraction of a period is occupied by the flame gases in rising from the orifice to the top of a flame when it is not singing.

When the flame is singing, the velocity of the gases is alternately greater and less than that for the silent flame, and it is difficult to know the amount by which the velocity changes. At the top of a steady flame the burning is proceeding downward at the same rate at which the flame gases are rising. If the amplitude of the alternating component of the velocity were equal to the velocity v_0 in the steady flame, the minimum upward velocity would be zero, and the minimum level of the top of the flame would probably be down near the orifice. For the top of the flame to go down into the gas tube, as it has sometimes been observed[12, 13, 14] to do, the amplitude of the velocity would probably have to exceed v_0, so that the maximum upward velocity would be greater than $2v_0$. On the other hand, if the amplitude of the velocity were, say, not greater than $0.2v_0$, it is not likely that the top of the flame would go up and down to the considerable extent that it often does. I have not found any satisfactory way of estimating the amplitude of the alternating component of the velocity; but from the reasoning just given, and for the flames that I have examined, I have chosen $1.5v_0$ as perhaps a fair value for the maximum upward velocity.

The velocity thus obtained is as it would be in the absence of any draft in the air tube. The air tubes that I used were vertical, and the draft certainly decreased the time in which a given level was reached. A very rough calculation of the draft suggests that it probably did not exceed a quarter of the upward velocity without the draft. I have assumed that it has this value.

In the somewhat cumbersome way that I have outlined, I have calculated for various cases the fraction of a period that is occupied by the flame gases in rising from the orifice to the top of the flame. In making these calculations I have assumed, as indicated above, that when a flame is in front of the organ pipe the distance up to the first constriction is proportional to the height of the flame, and also that for a flame of given height the distance up to the first constriction is proportional to the impressed period of vibration. These assumptions are most nearly fulfilled in cases where the singing flames are of heights similar to those used with the organ pipe and where the frequencies of the air tubes are not far from that of the organ pipe. I have, therefore, thrown out a number of cases—25 where singing occurred, and 38 where it did not—where these conditions were not very well satisfied, and have retained those cases in which (*a*) no flame had a height less than 2 cm, and (*b*) the frequencies of the air tubes differed from that of the organ pipe by not more than 11 percent. This selection gave me thirteen cases in which singing occurred and sixteen in which it did not. These were for two air tubes and fourteen orifices.

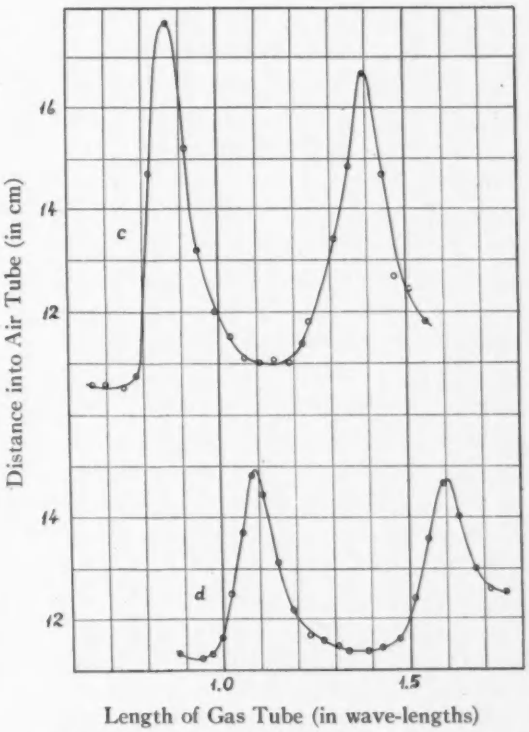


FIG. 3. Level to which a flame must be inserted into an air tube before singing is maintained. Curve *c* is for a 13-mm flame, with the gas tube connected directly to the gas cock. Curve *d* is for a 13-mm flame, with the gas tube ending below in an eight-liter flask.

If the hypothesis I have proposed is correct, the values for the time taken by the gases in rising to the top of the flame should be in the neighborhood of half a period when the flame sings, and quite different when the flame does not sing. For the thirteen flames that sang, the values run from $0.6T$ to $0.9T$, where T stands for the period of the vibration, and for the sixteen that did not sing they run from $1.2T$ to $3.3T$. In view of the various approximations made in reaching these values, I think we may at least say that there is no serious discrepancy between these results and my hypothesis.

Standing Waves

In order to examine the effect of standing waves I used the same air tube and gas orifice that I employed for curve *a* in Fig. 1, but now had the gas tube end below in an eight-liter flask. During part of this study the gas from the cock came to a Y, and from one side of the Y to the flask. The other side of the Y led to a flame from the same nozzle that I used for the external flame in the earlier work with a Y. In the present study I never detected any vibration in the external flame, and therefore conclude that the flask was of sufficient size.

For different lengths of gas tube the curves in Figs. 1 and 3 show the distances to which it was necessary to insert the flame into the air tube before it would sing. Curves *a* and *c* were taken with the gas tube connected directly to the gas cock, and *b*[32] and *d* with the gas tube ending in the flask. In all four curves there is a periodicity of the type to be expected from standing waves. The distances between maxima are in the neighborhood of half a wave-length, and in each figure the maxima of one curve fall between those of the other. This latter fact is what we should expect if in *b* and *d* the end of the gas tube in the flask is at an antinode, and in *a* and *c* the gas cock is at a node. Moreover, in all four curves the extent of the rise and fall of the curves decreases with increasing length of gas tube, showing that an increase in the length of the gas tube decreases the strength of the standing waves.

If the end of the gas tube in the flask really is at an antinode, and the gas cock, when the flask is not used, at a node, we should expect the maxima of curves *a* and *c* to lie close to a whole number of half-wave-length from the axis of ordinates, and those of *b* and *d* near odd numbers of quarter-wave-lengths. The positions of the maxima differ considerably from such values, probably because the wave-lengths have been calculated as if the temperatures in the air tube and gas tube were the same.

If we assume that the average temperature in the air tube for the 5 cm flame of curve *a* was 150°C, for the 2.8 cm flame of *b* was 130°C, and for the 13 mm flames of *c* and *d* was 100°C, the positions of the maxima for *a* are shifted to 0.99λ, 1.51λ, 1.99λ; for *b* to 1.25λ, 1.78λ; for *c* to 0.97λ, 1.57λ; and for *d* to 1.23λ, 1.80λ. These values are very satisfactory, and the temperatures chosen are entirely reasonable. In fact, at one time during the work readings of temperatures were taken with a thermocouple, and showed a temperature of about 200°C near the axis of the air tube and about 35 cm above a 5 cm flame, and of about 155°C in a similar location above a 3.3 cm flame.

Effect of Viscosity in the Orifice

The size of the flame is important. The 13 mm flames of curves *c* and *d* had to be introduced into the air tube to an average level of about 13 cm or 14 cm, the 2.8 cm flame of curve *b* to about 9.3 cm, and the 5 cm flame of curve *a* to about 8.2 cm.

These differences are explained by the change which the heat of the flame produces in the viscosity of the gas in the orifice. With a small flame the zone of most rapid combustion is at all times closer to the orifice than with a large flame, so that the viscous resistance in the orifice is greater, the amplitude of the change in velocity is decreased, and for singing to be maintained it is necessary that the flame be subject to greater variations in pressure. So a small flame has to be farther up in the air tube in order to sing.

The three experimental tests that have been described seem to give satisfactory support to the theory.

[32] When the observations for curve *a* were taken, the height of the flame remained most of the time beautifully constant at 5.0 cm. When the observations for *b* were taken, the flame varied irregularly from 2.7 cm to 3.1 cm, probably because of fluctuations in gas pressure or atmospheric pressure. This fact probably accounts for the greater scatter of the points for *b*.

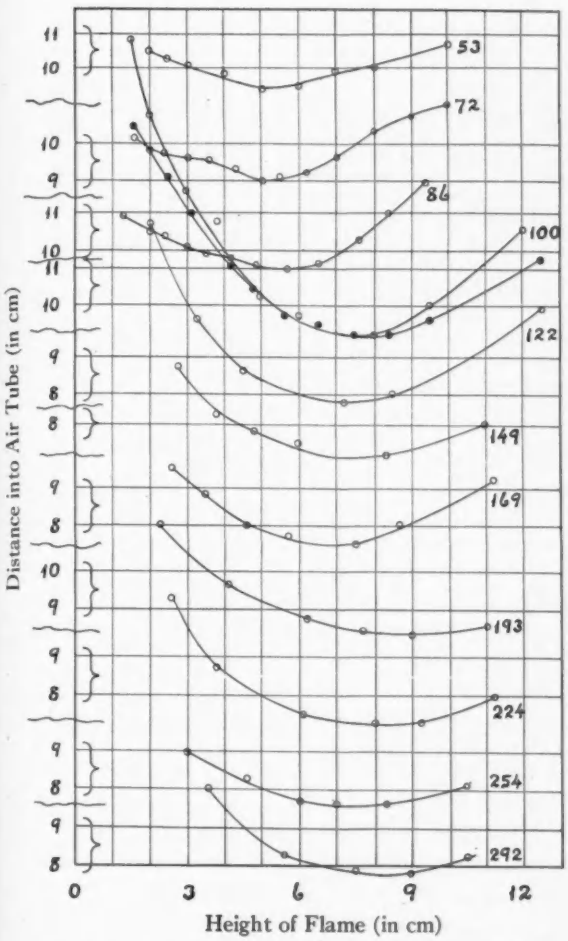


FIG. 4. Levels to which flames must be inserted in an air tube before singing is maintained, as a function of size of flame. Each curve is for one length of gas tube, and the numbers on the curves give these lengths (in cm). For all these curves the gas tube was connected directly to the gas cock. The black dots are for a repetition, about a week later, of the observations for the 100-cm curve.

EXPLANATION OF ADDITIONAL FACTS

Initiation of the Vibration

On Rayleigh's hypothesis and on the modification of it that I am proposing, it is assumed that there is already a small vibration in the air tube, and that the flame increases and maintains that vibration. It is known[8, 18, 26, 33] that when a flame is on the point of singing, an extraneous sound will often start it. The sound may be a musical tone of the proper pitch, or it may be as unmusical as that produced by moving a chair. When a flame is almost on the point of singing one easy means of starting it is simply to blow a gentle puff from the experimenter's mouth across one end of the air tube.

Frequently no obvious external sound is needed to start the singing, and the simplest explanation seems to be that there are always slight tremors in the air and that these are continually setting up inaudible vibrations in the air tube. Does it not seem a reasonable hypothesis that these minute vibrations are increased by the flame, and the spontaneous singing thus explained?

Size of Flame

In Fig. 4 are curves showing, for various lengths of gas tube, the distances that different sized flames must be inserted in an air tube before singing is maintained. How are these curves to be explained? In any small vibration in the air tube the pressure amplitude is greater at greater distances up toward the node. Now in a given time, as pointed out above, the gases in a flame rise to a greater fraction of the total height of the flame when the flame is small than when it is large. So if they rise to the top of the flame in the optimum fraction of a period for a certain height of flame, the time taken for a larger or smaller flame will be larger or smaller, the conditions for maintenance will be not quite as good, and the orifice will have to be introduced farther into the air tube—to a level at which the pressure is greater—before singing can be maintained. That is, we should expect the curves in Fig. 4 to exhibit minima, as they do.

To the left of a minimum, the flame gases probably rise to the top of the flame in less than half a period. If the time becomes less than something like a quarter of a period, the heat supply will be most rapid at a phase when the pressure is less than atmospheric, and so no maintenance is possible—at least for the fundamental mode of the air tube. But a quarter of a period for the fundamental is half a period for the octave. So the octave may be brought out. In fact, when a flame is small and is inserted a short distance, the octave is very likely to be heard rather than the fundamental. This fact was pointed out by Schaffgotsch[26] and by Banerji,[34] and I, too, have observed it. It is also known that

[33] W. F. Barrett, Chem. News **17**, 220 (1868).

[34] Durgadas Banerji, Proc. Ind. Assn. Cult. Sci. **7**, 47 (1921).

the regions in which the fundamental and the octave may be obtained overlap to some extent, and a region is often found in which the fundamental and the octave are of approximately equal loudness.

To the right of a minimum, the flame gases take a larger fraction of a period to reach the top of the flame. If the time becomes too long, the flame will not sing. This is in agreement with the known fact[21, 24, 29] that a large flame does not sing as readily as a smaller one and may even refuse to sing at all.

These statements do not contradict those made above in connection with the effect of viscosity in the orifice, for the height of the largest flame used for Figs. 1 and 3 was 5.0 cm, and the regions to the right of the minima in Fig. 4 are for larger flames.

Regions of Silence

The fact that small flames must be introduced into an air tube farther than larger ones before they will sing appears to be connected with the regions of silence discovered by Sondhauss.[18] In Fig. 3, with 13 mm flames, the rise and fall of the curves is much greater than in Fig. 1, where the flames were larger.

At one time I used a still larger flame, 5.5 cm tall, with the gas tube ending in the eight-liter flask, and found no definite evidence of any periodicity with changing length of gas tube. At another time I used a 10 mm flame, with the gas tube ending below in the flask; found the curves shifted upward, with the maxima rising considerably higher than those in either *c* or *d*; and found one narrow region, at the highest part of the curve, where I did not succeed in getting the flame to sing at all.

These facts suggest that with still smaller flames there would be lengths of gas tube for which the flame would not sing, and that the smaller the flames the wider would be the regions of silence. Richardson[2] says nothing about the size of the flames he used. Sondhauss[18] says that the height of his flames was usually only a few millimeters, and he also says that one method of getting a silent flame to sing is to change the size of the flame. Moreover, in much of his work Sondhauss used hydrogen, which has a high heat of combustion and therefore increases considerably the viscosity of the gas in the orifice. The discrepancy between experimenters who have found gaps in the lengths of gas tube for which a flame will sing and those who have not found these gaps, is probably to be explained on the basis of differences in the viscous resistance in the orifice—this resistance depending in part on the gas they employed and in part on the size of the flames they used.

Size of Orifice

It is known[2] that a flame will not sing when the orifice at which it burns is too small. A reason is probably to be found in the viscosity in the orifice. The smaller the orifice, the greater the viscous resistance and the smaller the amplitude of the velocity. Also, the shorter the air tube, the greater are the frequencies, and the more important the viscosity becomes.

I illustrate this effect and the effect of the size of the flame, by two orifices that I have used. Both are at the ends of brass tubes with a bore of 4.5 mm, and the orifices in both are cylindrical. In tube *A* the orifice is 9.5 mm long, and has a bore of 0.66 mm. In *B*, the corresponding dimensions are 1.59 mm and 0.49 mm. The flame from *A* sings well in air tubes 99 cm and 158 cm long. In an 83-cm tube a 1-cm flame sings, and a 2.4-cm flame does not sing. In a 50-cm tube no flame from this orifice sings. With the narrower orifice in *B*, I did not succeed in obtaining singing with any flame more than 5 mm high.

When the orifice is large the viscous resistance drops off, and the velocity often becomes so great that a flame which starts to sing is immediately put out.

Effect of Draft

A draft through the air tube increases the upward velocity of the flame gases, thus making it possible for them to rise to the top of the flame in a shorter time, and so making it possible for the flame to sing at a lower level in the air tube. This is doubtless the explanation of the effect I have mentioned above when the air tube was lifted from a horizontal to a vertical position.

The farther up the air tube the flame is, the shorter is the column of heated air and the weaker is the draft. Consequently we should

expect a flame to sing nearer to the lower end of the air tube than to the upper end, and I find that this expectation is fully justified with the flames I have usually employed, and that the effect is very marked.

If the flame is small, the draft is weak; and the region in which the flame sings may be expected to be nearly symmetrical about the node. This is what Sondhauss[18] found with the small flames that he employed. He also found that when the flame is causing the air tube to sing in its second, third, . . . seventh mode of vibration, there are two, three, . . . seven regions in which the flame maintains the singing and that these regions center around the positions of the corresponding nodes.

Rate of Rise of Top of Flame

When a singing flame is viewed in a rotating mirror, the motion of the top of the flame is usually seen to be far from simple harmonic. Very often it rises slowly and then drops quickly. This fact was pointed out by Töpler[13] and by Smith,[35] was noted again by Miss Porter,[25] and must have been observed by various persons who have looked at these flames in rotating mirrors. The contrary effect of a rapid rise and a slow fall has been reported in two papers,[2,12] but the rise is certainly the slower in the cases that I have observed, and the highest point of the flame is usually not reached until at least three quarters of a period after the lowest point.

The rising part of the curve is often remarkably close to a straight line.[36] The upward velocity of the flame gases decreases as they rise; but the top of the region of combustion probably moves downward, with respect to the gases, more slowly as the flame rises into the cooler air above it, and so nearly compensates the decreased upward velocity of the gases.

Before the flame has reached its greatest height the velocity of efflux decreases, so that the lower part of the flame tends to draw away from the upper, and the latter can burn out rapidly. The continued burning of the upper part of the flame after the lower part has withdrawn has actually been observed.[12,13,37]

Frequency

Sondhauss[18] noticed that when the flame is about half way up the air tube, the frequency is higher than when the flame is near the bottom of the tube. In some cases he found a rise in pitch of as much as a major second. A similar rise has been observed by Richardson,[2] and Würschmidt[29] has found that the frequency may deviate appreciably from the natural frequency of the air tube, even after allowing for the temperature of the air in the tube.

Carrière[21] points out that we are dealing with a coupled system, and this is no doubt the reason for the shift in frequency. A gas tube which opens into a flask has its own natural frequency, the air tube has its frequency, and each reacts on the other. Since the orifice which connects the two is small, the coupling is loose, and the frequency obtained is not far from that of the air tube.

Singing without a Gas Tube

The explanation of singing flames that has been advanced in this paper depends on a periodic change in pressure in the gas tube. But Peterin and Weiss[38] have found it possible to obtain flames that do not come from gas tubes and yet may sing when in air tubes. Peterin and Weiss burned alcohol, ether, turpentine, kerosene—sometimes with a wick that at the top spread widely, sometimes without any wick but at the top of a funnel that flared so as to give a considerable area of combustion. Flames from all of these sang to some extent in an air tube. They were even able to obtain singing when the flame came from a wick that had been coated with sulfur.

Rogers,[10] too, succeeded in obtaining "a very pure musical tone" with a flame from an alcohol lamp. By using a hollow wick, so that air could rise through the opening in the middle, and having the flame surrounded by an air tube, he obtained singing with alcohol, ether, and turpentine.

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[35] Francis H. Smith, Am. J. Sci. **45**, 421 (1868).

[36] For two beautiful photographs that show this effect with manometric flames see Louis W. Austin, Phys. Rev. **12**, 121 (1901).

[37] K. Marbe and M. Seddig, Ann. d. Physik **30**, 579 (1909).

[38] Julius Peterin and Edmund Weiss, Sitz. Wien. Akad., Math.-Physik. Classe **32**, 68 (1858).

The hypothesis that I have advanced does not cover such cases. When the draft is small, the flames considered earlier in this paper sing best near a node, and so depend primarily on the changing pressure in the air tube. A periodic change in pressure could hardly produce much effect on the flames just cited, and in these cases the explanation of the singing is probably to be sought in a combination of the alternating velocity in the air tube with the draft through it.

At a phase when the resulting upward velocity is large, the supply of air from below comes to the flame rapidly, and so increases the rate of combustion. The consequently increased rate of heat supply lags a little behind the upward velocity in the air tube, partly because the burning takes time and partly because the velocity in the flame lags somewhat behind that of the surrounding air. So the phase of maximum heat supply comes a little later than the phase of maximum upward velocity in the air tube. If the flame is in the lower part of the air tube, the maximum heat supply is therefore at a time when the pressure is above its mean value, and maintenance is possible. Thus the maintenance in the cases just mentioned is somewhat like that in a Rijke tube, although in a Rijke tube there is no flame when the tube is singing.

SUMMARY AND CONCLUSION

The principal new conclusions to be drawn from the above work may be summarized as follows:

(1) Standing waves in the gas tube are not essential for maintenance of the vibration in the air tube.

(2) It is possible for maintenance to occur when the phase of most rapid efflux of gas is quite different from that of maximum pressure in the air tube.

(3) The maintenance is dependent on the time taken by the flame gases in rising from the orifice to the top of the flame.

(4) The distance that the flame must be inserted in the air tube before maintenance occurs depends on the size of the flame.

(5) The viscosity of the heated gas in the orifice at which the flame burns plays an important role.

Attenuation of Sound in Lined Circular Ducts

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IN 1939 Morse[1] gave a solution to the problem of the attenuation of sound in lined rectangular and circular ducts. For the case of rectangular ducts the complete theory and graphs were given. However, for the case of circular ducts the theory only was given. The recent publication of tables[2] of Bessel's functions for complex arguments now makes feasible the construction of tables and graphs for the calculation of sound attenuation in lined cylindrical ducts. It is the purpose of this paper to provide such tables and graphs.

THEORY

For purposes of clarity, a brief development of the basic theory is given.

Differential equation:

$$\nabla^2 p=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 p}{\partial^2\Phi}+\frac{\partial^2 p}{\partial x^2}=\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}; \quad (1)$$

for the case of axial symmetry $\partial p/\partial\Phi=0$ and (1) reduces to

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right)+\frac{\partial^2 p}{\partial x^2}=\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}. \quad (2)$$

Boundary condition:

$$Z=p/u \qquad (r=a_0). \quad (3)$$

Solution:

The solution of (2) can be shown by the method of separation of variables[3] to be

$$p(r,x,t)=\sum_{n=0}^{\infty} P_n J_0\left[(\mu_n+i\kappa_n)\frac{\pi r}{a_0}\right]\cdot\exp\left[i\omega t-\frac{\omega}{c}(\sigma_n+i\tau_n)x\right]; \quad (4)$$

$$u(r,x,t)=\left(\frac{-i}{\rho c\eta}\right)\sum_{n=0}^{\infty}(\mu_n+i\kappa_n)P_n J_1\left[(\mu_n+i\kappa_n)\frac{\pi r}{a_0}\right]\cdot\exp\left[i\omega t-\frac{\omega}{c}(\sigma_n+i\tau_n)x\right]. \quad (5)$$

The Fourier-Bessel coefficients P_n are calculated in the usual manner so that Eq. (4) satisfies the initial conditions of the problem. The terms μ_n and κ_n are determined by the boundary conditions. Each term in Eqs. (4) and (5) is called a normal mode and must satisfy boundary condition (3). Thus μ_n and κ_n are the successive roots of the transcendental equation:

$$\frac{Z}{\rho c\eta}=\frac{\pi i}{\pi(\mu+i\kappa)}\cdot\frac{J_0\pi(\mu+i\kappa)}{J_1\pi(\mu+i\kappa)}, \quad (6)$$

where μ_n and κ_n are Morse's distribution parameters and the relation between them and his transmission parameters σ_n and τ_n can be found by substitution of the general term of Eq. (4) in the differential Eq. (2). There is obtained:

$$(\sigma_n+i\tau_n)^2=\left[\frac{\mu_n}{\eta}+i\frac{\kappa_n}{\eta}\right]^2-1=(\epsilon_n+i\delta_n)^2-1; \quad (7)$$

and

$$\sigma_n=\frac{1}{\sqrt{2}}\{[(\epsilon_n^2+\delta_n^2)^2-2(\epsilon_n^2-\delta_n^2)+1]^{\frac{1}{2}}+[\epsilon_n^2-\delta_n^2-1]\}^{\frac{1}{2}}, \quad (8)$$

$$\tau_n=\frac{1}{\sqrt{2}}\{[(\epsilon_n^2+\delta_n^2)^2-2(\epsilon_n^2-\delta_n^2)+1]^{\frac{1}{2}}-[\epsilon_n^2-\delta_n^2-1]\}^{\frac{1}{2}}. \quad (9)$$

Morse[1] gives a chart (his Fig. 1) which permits σ and τ to be read directly. This may be used in place of Eqs. (8) and (9).

It has been shown[1] that the attenuation in db/ft. is given by

$$D_n=\frac{54.574}{c}\sigma_n\nu=0.04836\sigma_n\nu, \quad (10)$$

[1] P. M. Morse, J. Acous. Soc. Am. 11, 205 (1939).
[2] *Table of the Bessel Functions $J_0(z)$ and $J_1(z)$ for Complex Arguments* (Columbia University Press, 1943).
[3] W. E. Byerly, *Fourier's Series and Spherical Harmonics* (Ginn & Company, New York, 1893), p. 12.

where c = speed of sound, ft./sec. = 1128.6; (760 mm, 20°C).[4] Equation (10) gives the attenuation corresponding to the nth mode of vibration, in terms of the frequency and transmission parameters. Since consideration of the first mode is usually sufficient for practical attenuation calculations, tables and charts are given for this mode only.

The Bessel function tables[2] which were used for this work give the argument in the complex exponential form. Hence the following transformation was made:

$$\pi(\mu+i\kappa)=Re^{i\theta}. \tag{11}$$

Equations (6) and (8) become:

$$\frac{Z}{\rho c\eta}=\frac{\pi i}{Re^{i\theta}}\frac{J_0(Re^{i\theta})}{J_1(Re^{i\theta})}; \tag{12}$$

$$\sigma_n=\frac{1}{\sqrt{2}}\left\{\left[\left(\frac{R}{\pi\eta}\right)^4-2\left(\frac{R}{\pi\eta}\right)^2\cos 2\theta+1\right]^{\frac{1}{2}}+\left[\left(\frac{R}{\pi\eta}\right)^2\cos 2\theta-1\right]\right\}^{\frac{1}{2}}. \tag{13}$$

The working formulas used in the construction of the Riemann surface for the first mode were:

$$\frac{Z}{\rho c\eta}=\frac{|Z|}{\rho c\eta}e^{i\phi}, \tag{14}$$

$$J_0(Re^{i\theta})=u_0+iv_0, \tag{15}$$

$$J_1(Re^{i\theta})=u_1+iv_1, \tag{16}$$

$$\frac{|Z|}{\rho c\eta}=\frac{\pi}{R}\left[\frac{u_0^2+v_0^2}{u_1^2+v_1^2}\right]^{\frac{1}{2}}, \tag{17}$$

and

$$\phi=\frac{\pi}{2}-\theta+\tan^{-1}\left(\frac{v_0}{u_0}\right)-\tan^{-1}\left(\frac{v_1}{u_1}\right). \tag{18}$$

For a given value of R and θ, u_0, v_0, u_1, and v_1 were read to five decimals from the table.[2] These values were converted into the exponential form by the use of tables.[5] The absolute values and amplitudes so determined were substituted in Eqs. (17) and (18) and $|Z|/\rho c\eta$ and ϕ computed. It is estimated that the final quantities $|Z|/\rho c\eta$ and ϕ are correct to three significant figures with some uncertainty in the fourth.

SERIES EXPANSIONS AND APPROXIMATION FORMULAS

Some useful formulas may be obtained by using the series expansions for Bessel functions in Eq. (12). Putting $Re^{i\theta}=z$, writing the series for $J_0(z)$ and $J_1(z)$, carrying out the indicated division and replacing z by $R(\cos\theta+i\sin\theta)$ there results:

$$\frac{Z}{\rho c\eta}=\frac{2\pi}{R^2}\{[(1+bR^4)\sin 2\theta+cR^6\sin 4\theta+dR^8\sin 6\theta+\cdots]-i[aR^2-(1-bR^4)\cos 2\theta+cR^6\cos 4\theta+dR^8\cos 6\theta+\cdots]\}. \tag{19}$$

Convergent for $(0<R<3.8317\cdots)$[6] where

$$a=1.25000\times10^{-1},$$
$$b=5.20833\times10^{-3},$$
$$c=3.25521\times10^{-4},$$

and

$$d=2.17014\times10^{-5}.$$

Equation (19) can be put in the form:

$$\frac{|Z|}{\rho c\eta}=2\pi\sqrt{2}\left\{\frac{1}{2}\left(\frac{1}{R^4}+a^2+b^2R^4+c^2R^8+d^2R^{12}+\cdots\right)+\left(\frac{a}{R^2}+abR^2+bcR^6+cdR^{10}+\cdots\right)\cos 2\theta+(-b+acR^4+bdR^8+\cdots)\cos 4\theta+(-cR^2+adR^6+\cdots)\cos 6\theta+(-dR^4+\cdots)\cos 8\theta+\cdots\right\}^{\frac{1}{2}}. \tag{20}$$

$$\tan\phi=\frac{-[aR^2-(1-bR^4)\cos 2\theta+cR^6\cos 4\theta+dR^8\cos 6\theta+\cdots]}{(1+bR^4)\sin 2\theta+cR^6\sin 4\theta+dR^8\sin 6\theta}. \tag{21}$$

[4] P. M. Morse, *Vibration and Sound* (McGraw Hill Book Company, Inc., New York, 1936), p. 188.
[5] J. C. P. Miller, *Tables for Converting Rectangular to Polar Coordinates* (Dover Publications, 1939).
[6] T. J. Bromwich, *An Introduction to the Theory of Infinite Series* (The Macmillan Company, New York, 1942), p. 154 and 264.

The following approximation formulas may be obtained from Eqs. (20) and (21).

$$|Z|/\rho c\eta \approx 2\pi/R^2; \tag{22}$$

$$\phi \approx \pi/2 - 2\theta; \tag{23}$$

$$R \approx \left[\frac{4\pi^2}{\left(\frac{|Z|}{\rho c\eta}\right)^2 + 4\pi a \frac{|Z|}{\rho c\eta}\cdot\sin\phi + 4\pi^2 a^2}\right]^{\frac{1}{2}}; \qquad (a = 0.125); \tag{24}$$

$$\theta \approx \tfrac{1}{2}\tan^{-1}\left(\frac{\frac{|Z|}{\rho c\eta}\cdot\cos\phi}{\frac{|Z|}{\rho c\eta}\sin\phi + 2\pi a}\right). \tag{25}$$

The approximate shapes in the $|Z|/\rho c\eta$, ϕ plane of the curves R = constant and θ = constant may be obtained from Eq. (19). To a first approximation:

$$\frac{Z}{\rho c\eta} \approx \frac{2\pi}{R^2}\sin 2\theta - \frac{2\pi}{R^2}(aR^2 - \cos 2\theta)i = u + iv, \tag{26}$$

where

$$u = \frac{2\pi}{R^2}\sin 2\theta, \tag{27}$$

and

$$v = -\frac{2\pi}{R^2}(aR^2 - \cos 2\theta). \tag{28}$$

Eliminating θ from Eqs. (27) and (28):

$$u^2 + (v + 2\pi a)^2 \approx \left(\frac{2\pi}{R^2}\right)^2. \tag{29}$$

Eliminating R from Eqs. (27) and (28)

$$v \approx \left[\tan\left(\frac{\pi}{2} - 2\theta\right)\right]u - 2\pi a. \tag{30}$$

Equation (29) shows that the curves R = constant are approximately circles in the u, v plane with centers at $(0, -2\pi a)$ and radii $(2\pi/R^2)$. Equation (30) shows that the curves θ = constant are straight lines in the u, v plane with slope angle $(\pi/2 - 2\theta)$ and intercept $(-2\pi a)$. The shapes of these curves are identical in the u, v plane and the $|Z|/\rho c\eta$, ϕ plane since u and v are the rectangular coordinates corresponding to the polar coordinates $|Z|/\rho c\eta$, ϕ. Advantage was taken of these properties in the construction of the curves of Figs. 2 and 3.

USE OF CHARTS AND TABLES

It is intended that the charts (Figs. 1–3) be used primarily to determine the net points required by Eq. (31). They may also be used to obtain directly, approximate values of distribution parameters or impedances. For more accurate values Tables I–V, together with the interpolation formulas, should be used. There are two types of problems which can be solved by the use of the tables and charts, the direct and the inverse. The direct problem is, given the distribution parameters, the duct dimensions, and the frequency, find the lining impedance. The inverse problem—the one usually met in practice—is, given the lining impedance, the duct dimensions, and the frequency, find the rate of sound attenuation in the duct. The direct problem is solved by entering the tables at the appropriate value of R and θ and reading $|Z|/\rho c\eta$ and ϕ interpolating where necessary (see Table VI). For most purposes linear interpolation is sufficient. However if more accurate values are required use may be made of the table of Lagrangian interpolants[7] or Eq. (19).

The inverse problem may be solved in the following manner. The given values of $|Z|/\rho c\eta$

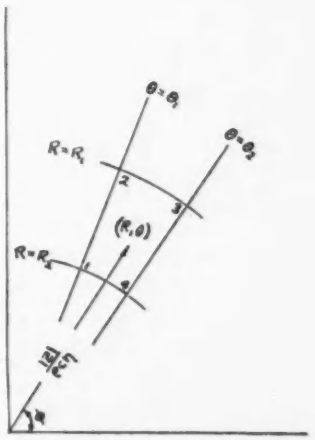

FIG. 1. Diagram showing net points 1, 2, 3, 4 surrounding point (R, θ).

[7] *Table of Lagrangian Interpolation Coefficients* (Columbia University Press, 1944).

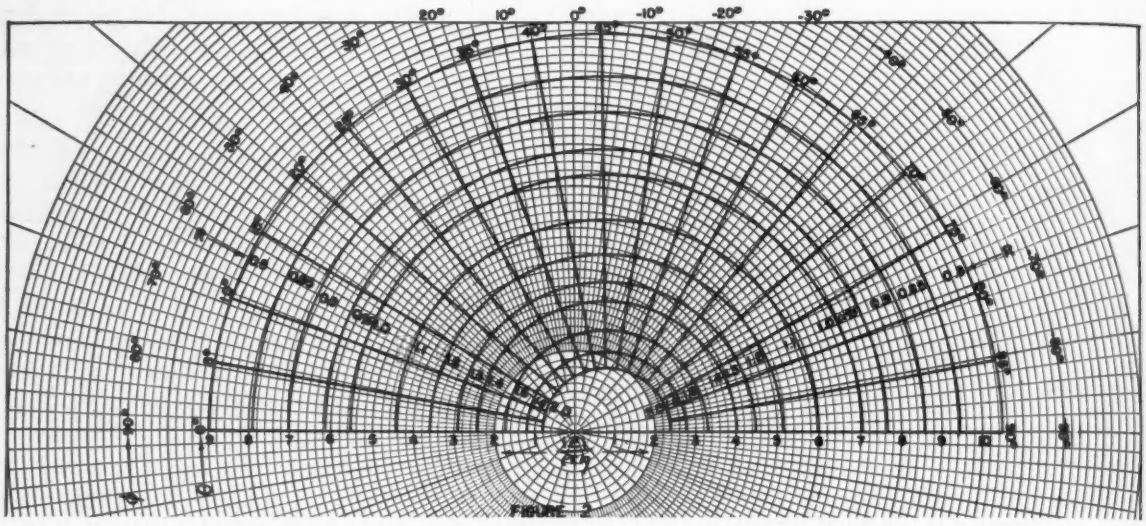

FIG. 2. Plot of the lines $R=$constant and $\theta=$constant in the $|Z|/ec\eta$, ϕ plane.

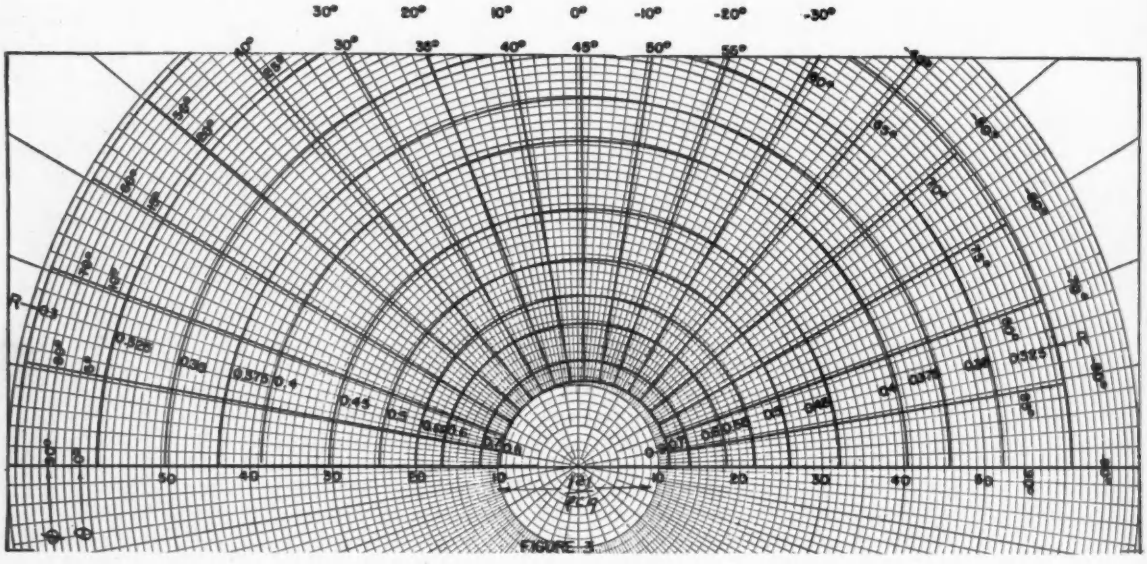

FIG. 3. Plot of the lines $R=$constant and $\theta=$constant in the $|Z|/\rho c\eta$, ϕ plane.

and ϕ are used to enter the chart (Fig. 2 or 3). The surrounding net points (see Fig. 1) (R_2, θ_1), (R_1, θ_1), (R_1, θ_2) and (R_2, θ_2) designated as 1, 2, 3, and 4 on the figure, are read from the chart. The corresponding values of $|Z|/\rho c\eta \equiv q$ and ϕ are read from the tables. The defining equations for the q's and the ϕ's are:

$$q=\frac{|Z|}{\rho c\eta}(R, \theta); \qquad \phi=\phi(R, \theta);$$

$$q_1=\frac{|Z|}{\rho c\eta}(R_2, \theta_1); \quad \phi_1=\phi(R_2, \theta_1);$$

$$q_2=\frac{|Z|}{\rho c\eta}(R_1, \theta_1); \quad \phi_2=\phi(R_1, \theta_1); \qquad (31)$$

$$q_3=\frac{|Z|}{\rho c\eta}(R_1, \theta_2); \quad \phi_3=\phi(R_1, \theta_2);$$

$$q_4=\frac{|Z|}{\rho c\eta}(R_2, \theta_2); \quad \phi_4=\phi(R_2, \theta_2).$$

R and θ may be computed from the following interpolation formulas:

$$R=R_2-\left[\frac{2q-q_1-q_4}{q_2+q_3-q_1-q_4}\right][R_2-R_1]; \quad (32)$$

$$\theta=\theta_1+\frac{1}{2}\left[\frac{\phi_1-\phi}{\phi_1-\phi_4}+\frac{\phi_2-\phi}{\phi_2-\phi_3}\right][\theta_2-\theta_1]. \quad (33)$$

TABLE I. Duct lining impedance as a function of distribution parameters.

R	$\theta=0°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=5°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=10°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=15°$ $\lvert Z\rvert/\rho c\eta$	ϕ
0.1	627.5	90.00	628.0	79.99	628.1	69.97	626.9	59.96
0.2	156.3	90.00	156.3	79.96	156.4	69.90	156.5	59.85
0.3	69.02	90.00	69.05	79.88	69.12	69.77	69.08	59.67
0.4	38.48	90.00	38.51	79.79	38.53	69.60	38.60	59.35
0.5	24.35	90.00	24.35	79.67	24.38	69.36	24.44	59.07
0.6	16.66	90.00	16.67	79.52	16.71	69.05	16.77	58.63
0.7	12.01	90.00	12.04	79.32	12.07	68.68	12.14	58.08
0.8	9.010	90.00	9.026	79.08	9.067	68.22	9.137	57.42
0.9	6.943	90.00	6.961	78.80	7.005	67.66	7.076	56.62
1.0	5.462	90.00	5.478	78.45	5.526	66.98	5.602	55.67
1.2	3.526	90.00	3.544	77.50	3.600	65.17	3.686	53.18
1.4	2.347	90.00	2.370	76.06	2.435	62.51	2.535	49.62
1.6	1.569	90.00	1.598	73.76	1.679	58.44	1.799	44.50
1.8	1.020	90.00	1.060	69.81	1.166	51.97	1.313	37.12
2.0	0.613	90.00	0.671	62.37	0.814	41.40	0.993	26.63
2.2	0.291	90.00	0.393	45.19	0.576	19.75	0.805	12.75

TABLE II. Duct lining impedance as a function of distribution parameters.

R	$\theta=20°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=25°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=30°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=35°$ $\lvert Z\rvert/\rho c\eta$	ϕ
0.1	627.1	49.95	627.3	39.95	627.6	29.91	627.8	19.93
0.2	156.7	49.82	156.5	39.77	157.1	29.74	157.0	19.74
0.3	69.24	49.58	69.32	39.50	69.35	29.43	69.59	19.59
0.4	38.66	49.24	38.76	39.10	38.89	28.99	39.04	18.91
0.5	24.52	48.80	24.64	38.57	24.75	28.41	24.88	18.29
0.6	16.86	48.25	16.96	37.98	17.08	27.69	17.21	17.51
0.7	12.23	47.57	12.34	37.13	12.46	26.80	12.59	16.60
0.8	9.229	46.73	9.338	36.17	9.463	25.77	9.595	15.51
0.9	7.170	45.75	7.285	35.04	7.412	24.56	7.547	14.27
1.0	5.702	44.58	5.824	33.75	5.951	23.17	6.089	12.86
1.2	3.797	41.59	3.925	30.48	4.063	19.79	4.205	9.501
1.4	2.661	37.52	2.801	26.19	2.947	15.56	3.091	5.495
1.6	1.942	32.02	2.095	20.78	2.247	10.49	2.393	0.904
1.8	1.476	24.78	1.640	14.18	1.795	4.69	1.937	−4.09
2.0	1.177	15.59	1.348	6.24	1.503	−1.55	1.637	−9.16
2.2	1.001	4.99	1.171	−1.52	1.315	−7.70	1.434	−13.94

TABLE III. Duct lining impedance as a function of distribution parameters.

R	$\theta=40°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=45°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=50°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=55°$ $\lvert Z\rvert/\rho c\eta$	ϕ
0.1	628.1	9.92	628.3	−0.065	628.6	−10.08	628.9	−20.07
0.2	156.8	9.71	157.1	−0.28	157.3	−10.28	157.6	−20.27
0.3	69.70	9.36	69.82	−0.64	69.94	−10.63	70.05	−20.60
0.4	39.16	8.87	39.29	−1.14	39.41	−11.12	39.53	−21.07
0.5	25.00	8.22	25.16	−1.79	25.29	−11.75	25.41	−21.65
0.6	17.34	7.43	17.48	−2.58	17.62	−12.50	17.75	−22.35
0.7	12.72	6.49	12.87	−3.50	13.00	−13.39	13.12	−23.19
0.8	9.733	5.40	9.871	−4.56	10.00	−14.39	10.13	−24.10
0.9	7.686	4.17	7.823	−5.75	7.955	−14.50	8.077	−25.12
1.0	6.228	2.78	6.364	−7.07	6.494	−16.72	6.615	−26.21
1.2	4.345	−0.43	4.478	−10.04	4.604	−19.42	4.718	−28.61
1.4	3.230	−4.12	3.360	−13.38	3.479	−22.38	3.584	−31.16
1.6	2.528	−8.19	2.651	−16.94	2.761	−25.43	2.857	−33.76
1.8	2.066	−12.46	2.179	−20.54	2.279	−28.47	2.366	−36.29
2.0	1.753	−16.59	1.853	−23.97	1.939	−31.34	2.016	−38.66
2.2	1.534	−20.41	1.619	−27.10	1.694	−33.96	1.760	−40.89

Formulas (32) and (33) are approximate interpolation formulas based on the assumption that, over the interval of interpolation, the lines $R=$ constant may be considered as circles and the lines $\theta=$ constant may be considered as radial lines. Lagrange's formula[8] for inverse interpolation in the complex plane may be applied but it is very tedious. There is no short method, known to the authors for calculating R and θ to a high degree of accuracy. If very accurate values of R and θ

TABLE IV. Duct lining impedance as a function of distribution parameters.

R	$\theta=60°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=65°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=70°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=75°$ $\lvert Z\rvert/\rho c\eta$	ϕ
0.1	629.1	−30.06	629.3	−40.05	629.5	−50.04	629.7	−60.03
0.2	157.9	−30.26	157.3	−40.22	157.5	−50.18	157.7	−60.15
0.3	70.14	−30.56	70.36	−40.49	70.40	−50.40	70.41	−60.30
0.4	39.67	−30.98	39.80	−40.87	39.89	−50.71	39.94	−60.56
0.5	25.53	−31.51	25.63	−41.33	25.7₂	−51.10	25.82	−60.86
0.6	17.87	−32.15	17.97	−41.88	18.06	−51.58	18.13	−61.20
0.7	13.24	−32.89	13.34	−42.52	13.43	−52.09	13.50	−61.61
0.8	10.24	−33.70	10.34	−43.22	10.42	−52.66	10.50	−62.05
0.9	8.190	−34.61	8.284	−43.98	8.368	−53.29	8.435	−62.52
1.0	6.722	−35.57	6.819	−44.80	6.896	−53.94	6.957	−63.02
1.2	4.819	−37.63	4.905	−46.52	4.977	−55.33	5.032	−64.06
1.4	3.677	−39.79	3.755	−48.31	3.820	−56.74	3.869	−65.11
1.6	2.941	−41.96	3.011	−50.07	3.042	−58.90	3.111	−66.13
1.8	2.439	−44.04	2.500	−51.74	2.550	−59.43	2.588	−67.07
2.0	2.081	−46.02	2.136	−53.34	2.179	−60.60	2.211	−67.91
2.2	1.817	−47.83	1.865	−54.75	1.902	−61.68	1.929	−68.64

TABLE V. Duct lining impedance as a function of distribution parameters.

R	$\theta=80°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=85°$ $\lvert Z\rvert/\rho c\eta$	ϕ	$\theta=90°$ $\lvert Z\rvert/\rho c\eta$	ϕ
0.1	629.8	−70.03	629.9	−80.02	629.9	−90.00
0.2	157.8	−70.10	157.8	−80.04	157.9	−90.00
0.3	70.51	−70.22	70.58	−80.11	70.61	−90.00
0.4	40.01	−70.38	40.03	−80.19	40.06	−90.00
0.5	25.87	−70.58	25.90	−80.30	25.91	−90.00
0.6	18.19	−70.83	18.22	−80.42	18.23	−90.00
0.7	13.55	−71.10	13.58	−80.56	13.59	−90.00
0.8	10.54	−71.39	10.57	−80.70	10.58	−90.00
0.9	8.479	−71.71	8.507	−80.86	8.517	−90.00
1.0	7.002	−72.04	7.029	−81.02	7.037	−90.00
1.2	5.073	−72.73	5.097	−81.37	5.106	−90.00
1.4	3.906	−73.43	3.927	−81.72	3.934	−90.00
1.6	3.143	−74.10	3.161	−82.05	3.167	−90.00
1.8	2.615	−74.72	2.631	−82.36	2.636	−90.00
2.0	2.233	−75.24	2.245	−82.60	2.249	−90.00
2.2	1.946	−75.69	1.955	−82.82	1.958	−90.00

TABLE VI. Comparison of $\lvert Z\rvert/\rho c\eta$, ϕ calculated by different methods for $R=0.65$, $\theta=22°$.

Method of computation	$\lvert Z\rvert/\rho c\eta$	ϕ
Linear interpolation	14.59	43.77°
Lagrangian interpolants	14.37	43.78°
Equation (19)	14.32	43.76°

[8] J. B. Scarborough, *Numerical Mathematical Analysis* (Johns Hopkins University Press, 1930), p. 73.

are required the following iteration process may be used. A first approximation (R_1, θ_1) is obtained by use of Eqs. (24) and (25). A second approximation (R_2, θ_2) is calculated by means of the formulas:

$$R_2=\left[\left(\frac{|Z|}{2\pi\rho c\eta}\right)^2-2\left\{\tfrac{1}{2}(a^2+b^2R_1^4+c^2R_1^8+d^2R_1^{12}+\cdots)\right.\right.$$
$$+\left(\frac{a}{R_1^2}+abR_1^2+bcR_1^6+dcR_1^{10}+\cdots\right)\cos 2\theta_1+(-b+acR_1^4+bdR_1^8+\cdots)\cos 4\theta_1$$
$$\left.\left.+(-cR_1^2+adR_1^6+\cdots)\cos 6\theta_1+(-dR_1^4+\cdots)\cos 8\theta_1+\cdots\right\}\right]^{-\frac{1}{4}}, \quad (34)$$

$$\sin 2\theta_2=-\frac{[aR_1^2-(1-bR_1^4)\cos 2\theta_1]\cos\phi+cR_1^6\cdot\cos(4\theta_1-\phi)+dR_1^8\cos(6\theta_1-\phi)}{(1+bR_1^4)\sin\phi}. \quad (35)$$

A third approximation (R_3, θ_3) is obtained by replacing R_1 and θ_1 in Eqs. (34) and (35) by R_2 and θ_2. This process may be continued until the desired accuracy is attained.

As an example illustrating the use of the charts and tables, the details of a typical duct calculation are given (see Table VII). R_1, R_2, θ_1, θ_2 are read from the chart. q_1, q_2, q_3, q_4, ϕ_1, ϕ_2, ϕ_3, ϕ_4 are read from the tables, in accordance with the definitions (31). Substituting in (32) and (33):

$$R=0.4167; \quad \theta=81.20°.$$

Using Eqs. (13) and (10):

$$\sigma=0.0612,$$
$$D=0.76 \text{ db/ft}.$$

The attenuation for the same duct system, calculated by the Sivian[10,11] method gives 0.71 db/ft.

TABLE VII. Calculation of attenuation at 256 c.p.s. in 10″ diameter duct lined with 1″ thickness Johns-Manville Sanacoustic pad.

$\lvert\hat{Z}\rvert/\rho c=7.117$;	$\phi=-72.82°$ [reference 9]
$\eta=2a_0\nu/c=(2\times5\times2.54\times256)/(3.44\times10^4)=0.1890$	
$\lvert Z\rvert/\rho c\eta=7.117/0.1890=37.66$	
$q=37.66$	$\phi=-72.82$
$q_1=25.87$	$\phi_1=-70.58$
$q_2=40.01$	$\phi_2=-70.38$
$q_3=40.03$	$\phi_3=-80.19$
$q_4=25.90$	$\phi_4=-80.30$
$R_1=0.4$	$\theta_1=80$
$R_2=0.5$	$\theta_2=85$

[9] L. Beranek, J. Acous. Soc. Am. 12, 14 (1940).

It is to be understood that the opinions or assertions contained in this paper are the private ones of the authors and are not to be construed as official or reflecting the views of the Navy Department or the Naval Service at large.

LIST OF SYMBOLS

r, x, Φ—Space coordinates (cylindrical)
t—Time
$p(r, x, t)$—Acoustical pressure at (r, x, t)
$u(r, x, t)$—Radial velocity at (r, x, t)
c—Speed of sound
Z—$|Z|e^{i\phi}$ acoustic impedance of duct wall lining (pressure/linear velocity)
a_0—Duct radius
$J_0(\beta)$, $J_1(\beta)$—Bessel functions of first kind, zeroth and first order respectively
μ, κ—Morse's[1] distribution parameters
σ, τ—Morse's[1] transmission parameters
ω—Circular frequency
ν—Frequency (c.p.s.)
η—Morse's frequency parameter $(=2a_0\nu/c=)$ (duct radius in half-wave-lengths). Morse[1] gives η as twice this value but this is a typographical error
ϵ—μ/η
δ—κ/η
D—Attenuation in given duct system (decibels/foot)
R, θ—Polar form of distribution parameters, defined by Eq. (11)
q—$|Z|/\rho c\eta$.

[10] L. J. Sivian, J. Acous. Soc. Am. 9, 135 (1937).
[11] C. T. Molloy, J. Acous. Soc. Am. 16, 31 (1944).

Kneser's Sound Absorption Nomogram and Other Charts

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THE author has been using Kneser's[1] nomogram ever since its publication several years ago, although for a time he had the impression that absorption values obtained by it were too low to conform with those observed and published by Knudsen.[2] This opinion has also been expressed by others. More than a year later the author plotted the maximum value of μ, the molecular absorption per wave-length, as a function of the temperature. Figure 1 shows how well Kneser's theoretical values and his observed values agree with Knudsen's observed values.

The deviations of Kneser's theoretical values from the smooth curve in Fig. 1 are due to the uncertainties in the quantities from which the theoretical values were calculated. At a fixed temperature the value of $\mu_{\max}$ is independent of the frequency, therefore $\mu_{\max}$ was selected for plotting rather than the maximum values of m_M where m_M is the molecular absorption per centimeter.

$$m_M=\mu/\lambda=\mu f/V \qquad (1)$$

(λ is the wave-length in cm. V is the velocity of sound in cm/sec., and f is the frequency.)

Figure 2 shows Kneser's nomogram with a minor correction ($\log \chi$ instead of $\log \alpha$) and a few additions, translations, extrapolations, etc.

By means of this nomogram the molecular absorption[2,3] can easily be found for any ordinary set of conditions of temperature, humidity, and sound frequency. For example, if the temperature is 15°C, the relative humidity is 50 percent and the frequency of the sound waves is 3 kc, then begin tracing at 15° on the temperature axis, trace left to the 50 percent mark, then upward to the middle of the shaded area (upper left), then to the right to the 3 kc curve, then downward to the $\log \chi/(1+\chi^2/f^2)$ scale. Next begin another tracing at 15°C toward the *right* until the lower right curve is reached, then trace upward to the $\log M+7$ scale. Now join the end points of the two tracings with a straight line. The value of m_M is now read as the encircled point of intersection with the m_M scale at $270(10)^{-7}$ per cm. The corresponding value of Δ_M is about 17 db/km or 0.003 db/ft. After this has been done m_c the absorption due to heat conduction and viscosity of the air can be found from Fig. 2a (inset of Fig. 2) by using the following relation,

$$m_c=A/\lambda^2=Af^2/V^2. \qquad (2)$$

Next use the relation

$$\Delta_c=132m_c \quad (\Delta_c \text{ in db/ft.}). \qquad (3)$$

The half-width of the shaded band in the log χ chart represents the uncertainty in log χ values. Note that the band changes position slightly with temperature.

The expected decrement, Δ_A, because of both types of absorption is the sum of Δ_M and Δ_c or

$$\Delta_A=\Delta_M+\Delta_c. \qquad (4)$$

Knudsen's[2] measurements in the audible range and others in the supersonic range show that the observed Δ_c exceeds its theoretical value by a factor ranging from 1.5 to 5, depending on humidity and frequency. Pumper[4] used a method in the supersonic range which gave better agreement. The writer's[5] measured value at 1215 kc is 1.1 times the theoretical value.

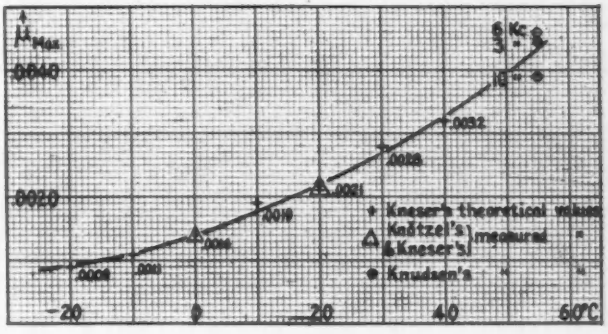

FIG. 1.

[1] H. O. Kneser, Akust. Zeits. **5**, 256 (1940).
[2] V. O. Knudsen, J. Acous. Soc. Am. **5**, 112 (1933).
[3] Helmuth Knötzel, Akust. Zeits. **5**, 245 (1940).
[4] E. J. Pumper, J. Phys. USSR **1**, 411 (1939).
[5] W. H. Pielemeier, Phys. Rev. **34**, 1184 (1929).

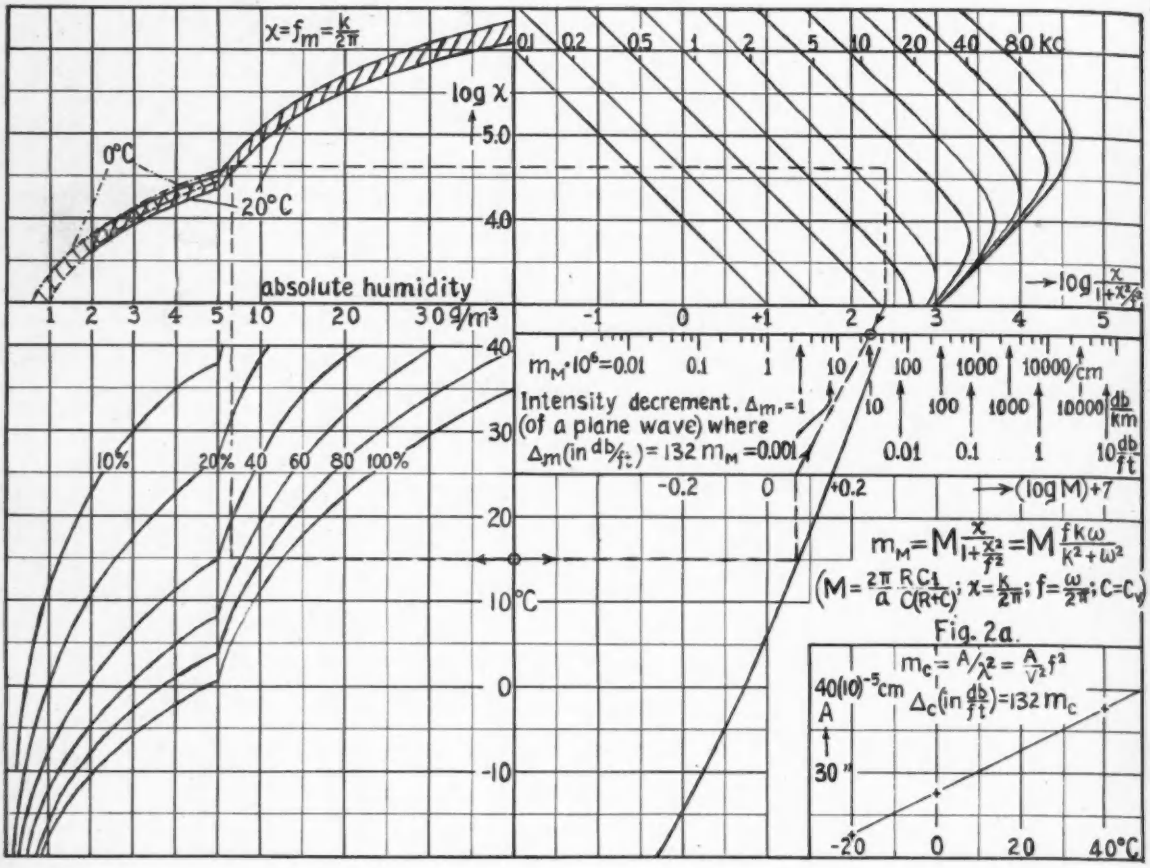

FIG. 2.

With most experiments in the audible range the waves diverge so there is an added decrement as indicated by the inverse square law. Figure 3 shows a method of plotting calculated intensity levels (above 10^{-16} watt/cm^2) as a function of x, the distance from a source, when this kind of decrement and also that represented by $\Delta_A=\Delta_M+\Delta_c$ occur. The author devised this method about the time he began using Kneser's nomogram. Similar methods are now being used by others.

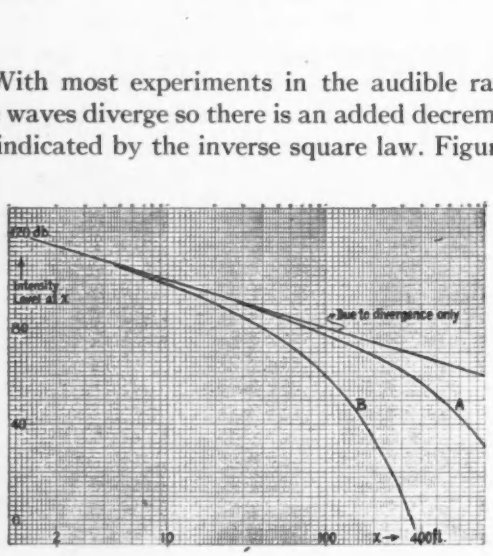

FIG. 3.

Two values of Δ_A are represented in Fig. 3. For Curve A $\Delta_A=0.029$ db/ft. (20 kc at 30°C, 80 percent, R. H.); for Curve B $\Delta_A=0.22$ db/ft. (20 kc at 30°C, 15 percent, R. H.). The divergence decrement is shown also.

Since observed decrements are rarely as small as the expected ones there must be agencies present which divert some of the energy from the path taken by the sound energy in going from the source to the receiver.

R-C Filter Circuits

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(Received February 12, 1945)

INTRODUCTION

THE limitations of L-C filters at low frequencies arise from the facts that the Q of an inductance becomes very low and the condensers of the required capacity are often as bulky as the inductances. The problem in R-C filters is one of getting the desired sharp cut-off features. In this paper an attempt is made to solve this problem with R-C components whose size would not be excessive even at frequencies as low as one cycle per second.

HIGH-Q R-C CIRCUITS

The present method of obtaining a relatively sharp cut-off involves a parallel T-network of condensers and resistances as shown in Fig. 1. The Q of this network, as is generally true of R-C bridges, is very low but may be greatly increased by negative feedback.

By transforming each T-network to the equivalent delta-network and then combining the two it may easily be shown that the equivalent delta-network is as shown in Fig. 2, where X represents the impedance due to the capacity C. The output of this circuit will be given by

$$(R^2-X^2)/(R^2-X^2-4jRX). \quad (1)$$

Hence, the phase is

$$\theta=\tan^{-1} 4RX/(R^2-X^2). \quad (2)$$

In Figure 3 is plotted the output of an actual T-network (hereafter simply referred to as T) together with the phase. The output should be symmetrical about the resonance point, but since measurements were made with a relatively low impedance voltmeter, higher readings were obtained at higher frequencies where the output impedance of the T is lower.

Consider now an amplifier with a gain of μ followed by a T of whose output a fraction β is fed back negatively to the amplifier. The effective gain without feedback is now

$$\mu(R^2-X^2)/(R^2-X^2-4jRX).$$

Hence, the gain with feedback is

$$G=\mu(R^2-X^2)/[(R^2-X^2)(1+\mu\beta)-4jRX]. \quad (3)$$

For the absolute value of G we have

$$\begin{aligned}|G| &= \mu(R^2-X^2)/[(R^2-X^2)^2 \\ &\qquad \times(1+\mu\beta)^2+16R^2X^2]^{\frac{1}{2}} \\ &= \mu(R/X-X/R)/[(R/X-X/R)^2 \\ &\qquad \times(1+\mu\beta)^2+16]^{\frac{1}{2}}. \quad (4)\end{aligned}$$

Near the resonance point where R is nearly equal to X the denominator becomes simply $=4$; hence, $|G|=(\mu/4)(R/X-X/R)$, and the shape of the curve is the same as for a simple T (see Eq. (1)). But when we are an octave or more away from resonance $(R/X-X/R)$ will always be greater than unity and so, for any reasonable value of $\mu\beta$, the denominator will be very nearly

$$\beta\mu(R/X-X/R),$$

and hence,

$$|G|=1/\beta.$$

Thus the sharpness of the resonance has been

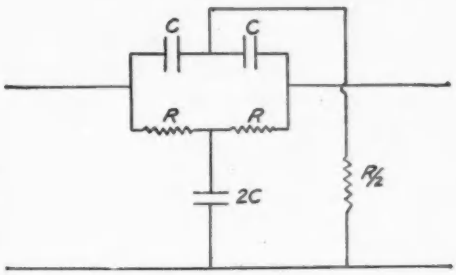


FIG. 1. Parallel T network.

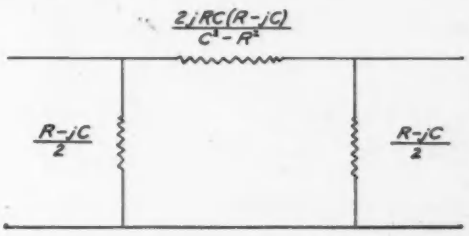


FIG. 2. Delta network equivalent to the T network in Fig. 1. Where C occurs in Fig. 2, X should be used in its stead.

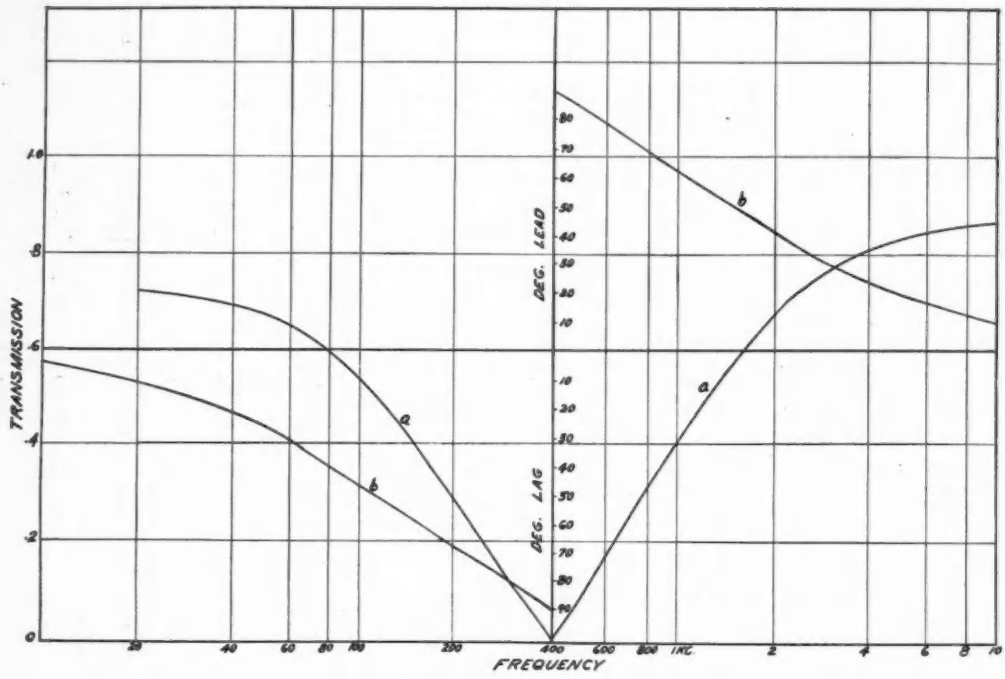


FIG. 3. (a) Output of an actual T network for one-volt input. (b) Corresponding phase in degrees, as calculated from Eq. (2).

greatly increased. Figure 4a gives the transmission of a T when used with one high mu triode, using feedback as shown in Fig. 6, but with R_1, C_1, and C_2 out of the circuit. The transmission does not go to zero at resonance, because the signal comes through the feedback network. This will often be a serious drawback and may be avoided by using the T between two tubes and putting the feedback to the cathode of the first tube. The μ in this case will be much greater and as is obvious from Eq. (4) the sharpness of the resonance will depend on μ when β is constant. This may be very useful in the design of a high-Q wave trap as for instance to eliminate hum in amplifiers. Figure 5 shows the result when a T was used between two pentodes with enough feedback applied to reduce the overall gain to 20.

LOW PASS FILTER

From Eq. (2) we see that for X approaching R we have a 90° phase shift which is positive or negative depending on whether $R>X$ or $R<X$ (see Fig. 3). If we now add a reactive component to the load of the tube by shunting the plate to ground by means of a condenser C_2 we introduce a further phase lag. On the low frequency side of resonance we will then have a positive component of feedback which will show itself in a slight hump before the gain suddenly drops. On the high frequency side of resonance the gain will never come up to normal since the condenser C_2 begins to reduce the load impedance considerably. In Figure 4 the dotted curve is one obtained with the circuit in Fig. 6, where $C_2=0.03$ microfarad

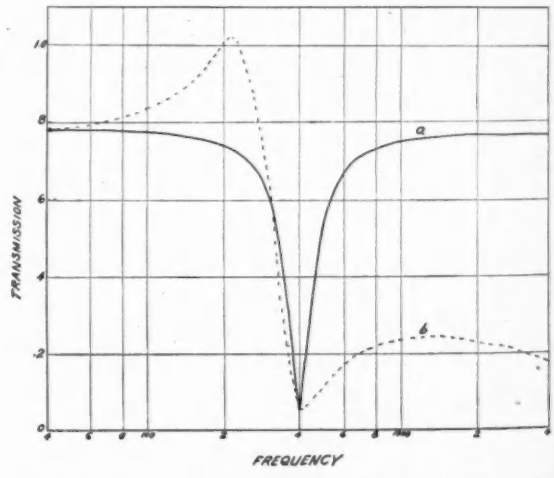
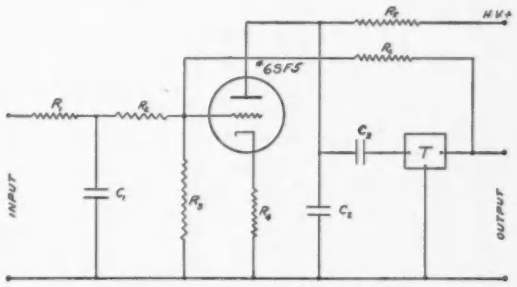


FIG. 4. (a) Output of circuit in Fig. 6 when R_1, C_1, and C_2 are removed. (b) Output of the same circuit with only R_1 and C_1 removed.

and R_1 and C_1 were not in the circuit. We have thus obtained a sharp drop in gain, but the ratio is as yet not very great.

The hump shown in Fig. 4 is of course not desirable and may be flattened by introducing R_1 and C_1 into the circuit. Figure 6 represents our basic circuit for all subsequent filters and its characteristics are shown in Fig. 7. The gain is very flat up to 220~. At 400~ it is down to 8 percent and never rises above that value.

To get a greater attenuation it is only necessary to put another circuit in series and this was actually done. The only modification consisted of changing R_1 and C_1 in the second basic circuit to 0.2 megohm and 0.005 mf respectively, so that it would not load the first filter too much. The effect



R_1— 100,000 ohms
R_2— 400,000 ohms
R_3—2,000,000 ohms
R_4— 1,500 ohms
R_5— 100,000 ohms
R_6— 400,000 ohms

C_1—.01 mf
C_2—.03 mf
C_3—.20 mf. This condenser may be put after the T and its value considerably reduced.

FIG. 6. Basic filter circuit.

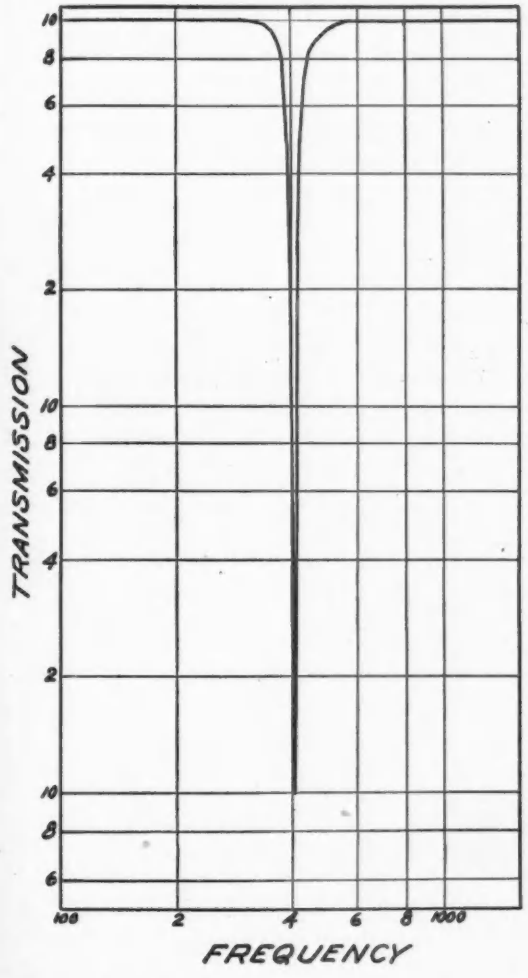


FIG. 5. Transmission characteristics of a T between two pentodes with negative feedback enough to reduce gain to 20.

of excessive loading is to widen the hump, which can then not be flattened as well. The result of this double circuit is given in Fig. 8. Actually C_1 was trimmed to 0.0045 mf to adjust the gain at 200~ to be equal to the gain at low frequency. For comparison purposes the dotted line shows the cut-off for a typical constant-K filter (consisting of two T-sections with a cut-off at 2000~). In the initial drop-off the L-C filter is superior to the R-C filter and may be made more so by using permalloy coils with a higher Q. But in the region of one octave from the cut-off frequency the attenuation for the R-C filter is greater. While the R-C filter output comes to another maximum this never rises above $\frac{1}{2}$ percent and is therefore not of any great importance.

HIGH PASS FILTER

The basic circuit for a high pass filter does not differ greatly from that discussed above. Instead of retarding the phase we now wish to advance it so that the positive feedback will occur at the high frequency side of resonance. This is done by simply decreasing the size of the coupling condenser C_3 and putting a resistance R_7 to ground after it, so that C_3 will see an impedance equal to R_7 and with not too great a reactive component. This will now result in something resembling a mirror image of 4b and again we decrease the hump by introducing R_1 and C_1 but in reversed position. The transmission characteristics of two such sections in series are given in Fig. 9. While in principle the problem here is identical to that of the low pass filter, in practice there are minor differences. In the low pass filter the load in the

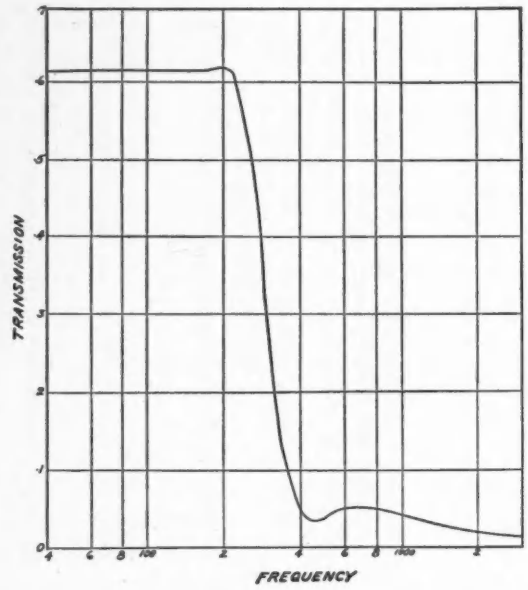


FIG. 7. Transmission of basic filter circuit of Fig. 6 with one-volt input.

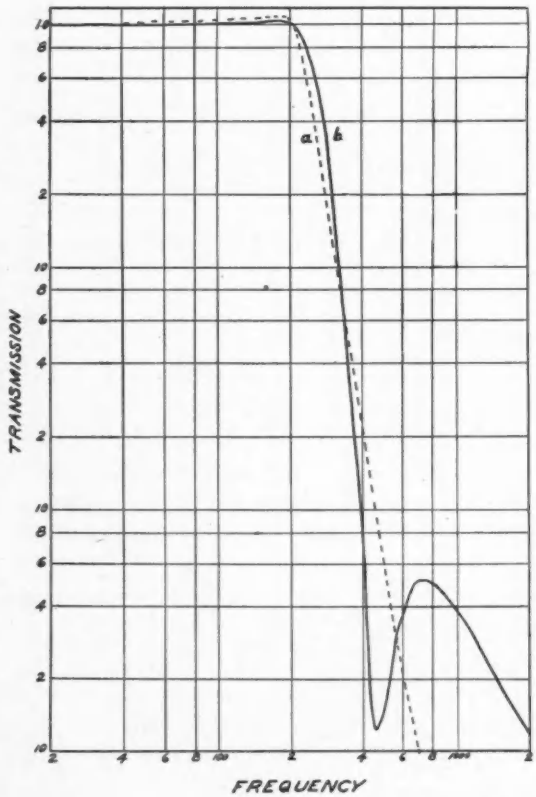


FIG. 8. Output in percent of low frequency output for L-C and R-C filters. (a) Two T sections of a constant-K filter with cut-off at 2000 c.p.s. (b) Two sections of basic circuit shown in Fig. 6 with cut-off at 200 c.p.s.

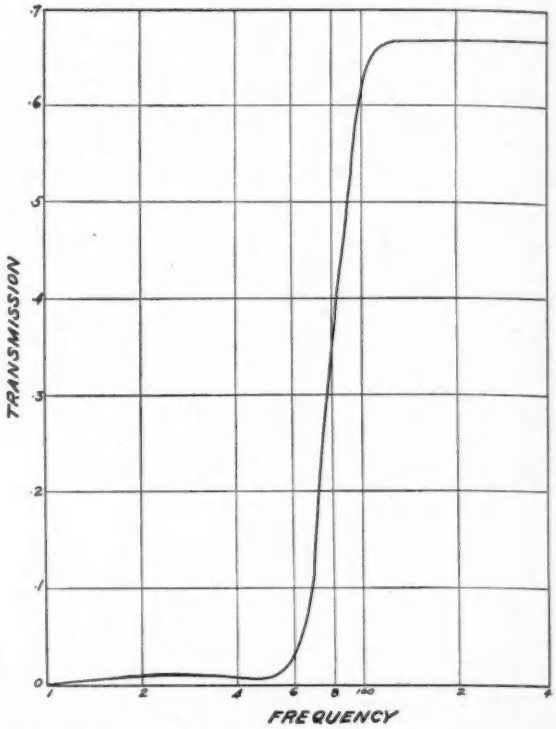


FIG. 9. Transmission of two sections of basic high pass R-C circuit with a cut-off at 100 c.p.s. Input is one volt.

pass-band is simply R_5 in parallel with T. In the high pass filter the load is R_5 in parallel with R_7 and T. This reduces the gain and broadens the curve corresponding to Fig. 4a. To counteract this R_5 was increased to 200,000 ohms. Also, R_2 and R_6 were changed to 1.0 megohm and R_1 to 400,000 ohms with C_1 reduced in a corresponding manner.

BAND-PASS FILTER

Nothing new is involved in a band-pass filter but for the sake of completeness a bread-board circuit was hooked up using the above low pass filter and a high pass filter tuned to 50~ and hence starting to cut off at 100~. The result is given in Fig. 10.

DISCUSSION

A word of caution may be in place at this point. Since tubes are involved there is a definite limit to the output amplitude and this limit is quite low. In Fig. 11 are plotted the signals at the plates of the two tubes involved in the low pass

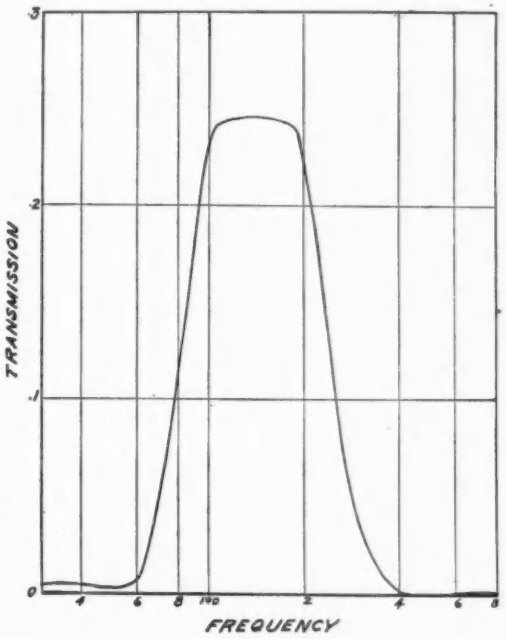


FIG. 10. Transmission in volts of R-C band-pass filter with one-volt input.

filter, as a function of frequency, with one volt as the input signal. When we consider that the transmission in the pass band is of the order of 0.3 volt while the maximum swing on the plate of the first tube is 3.3 volts, then it becomes obvious that overloading may easily become a problem in band-pass filters. It would probably often be desirable to introduce an amplifier tube between sections especially where amplification is required for other reasons. This would have the further advantage that the filter stage would feed a grid rather than another filter. The impedance of the T used is of the order of 0.2 megohm and so the following filter is a fairly heavy load on it. This is best seen by comparing the top edge of the curve in Fig. 7 with those in Fig. 10 where almost all sections are fairly heavily loaded.

A study of the results given shows that L-C filters are left complete masters in their field. Not only are the shapes of the curves superior but the number of components involved is smaller. However, at low frequencies both advantages are lost, and R-C filters begin to assert themselves. When we get much below 100~ there is no longer any choice left, and we must resort to R-C components. It is in this region that it is hoped this discussion will be most useful.

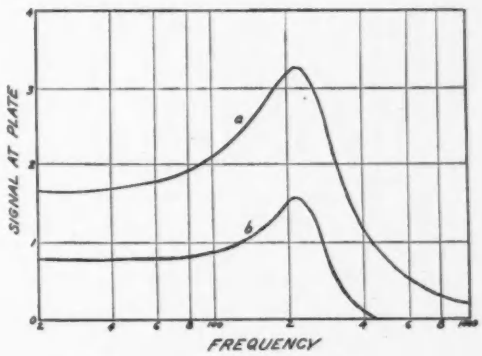


FIG. 11. (a) Signal at the first plate of the two-section low pass filter when input is one volt. (b) Signal at second plate with the same input.

Erratum

In the paper "Some Experimental Evidence for Peripheral Auditory Masking" by Karl Lowy in the January, 1945 issue of this journal, page 197, Figs. 10 and 14 of pages 200 and 201 are interchanged; the figure labeled 10 is really 14, and vice versa. It is important to mark this change in your copy of that paper, since without it some of the text is unintelligible.

Acoustical Society News

Clinton R. Hanna Named Associate Director of Westinghouse Research

Clinton R. Hanna, manager of the electro-mechanical department of the Westinghouse Research Laboratories, has been appointed an Associate Director of the Laboratories, it was announced by Dr. L. W. Chubb, Director of Research.

For his work in the development of the tank gun stabilizer, which enables Allied tanks to fire accurately while in motion, he was awarded a Presidential Citation in 1942. A holder of more than 80 patents, Mr. Hanna's work also includes the design of the silverstat, an automatic voltage regulator, and the development of the photophone, one of the first successful methods of producing talking movies.

Born on December 17, 1889 in Indianapolis, Indiana, Mr. Hanna attended Purdue University where he was graduated in 1922 with the degree of bachelor of science in electrical engineering, receiving the professional degree of electrical engineer four years later.

He is a member of the Institute of Radio Engineers and a fellow of the Acoustical Society of America and the American Institute of Electrical Engineers, and has contributed more than a score of papers to technical journals.

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Mechanical Engineering Department

Current Publications on Acoustics

F. A. FIRESTONE
3059 Randall Laboratory, University of Michigan, Ann Arbor, Michigan

References to Contemporary Papers on Acoustics

MOST of the titles of papers appearing in other languages than English have been translated. Abstracts in English of many foreign papers have appeared or soon will appear in Science Abstracts, Section A. Where references are made to Science Abstracts, the reference is to the volume number and abstract number. The abbreviations of the names of journals are those used in Science Abstracts and can be found in any annual index to those abstracts.

The numbers appearing at the head of each entry are the numbers which identify the subject headings in the Cumulative Index of this Journal issued in November, 1939. The same Classification of Subjects can be found in the index to Volume 15.

Compiled with the generous assistance of Samuel Sass, Physics Librarian, University of Michigan.

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11.7 **On the Elastic Vibrations of Cylindric Shells.** P. S. EPSTEIN. Bull. Amer. Phys. Soc. (Dec. 6, 1943); Sci. Abs. **A47**, 1289 (1944).

11.8 **Apparatus and Technique for Measurement of Vibratory Threshold and of Vibratory "Adaptation" Curve.** C. D. ARING AND W. O. FROHRING. J. Lab. Clin. Med. **28**, 204–207 (Nov. 1942); Sci. Abs. **A47**, 1295 (1944).

11.8 **Human Susceptibility to Vibration.** F. POSTLETHWAITE. Engineering **157**, 61–63 (Jan. 28, 1944); Sci. Abs. **A47**, 1297 (1944).

Review of Acoustical Patents

ROBERT W. YOUNG
C. G. Conn, Ltd., Elkhart, Indiana

Patents reviewed below have been issued by the United States Patent Office on the dates indicated. Printed copies may be obtained from the Commissioner of Patents, Washington, D. C. at a cost of 10¢ each. Remittance may be made by money order, check, cash, or special coupons which are sold in blocks of twenty or books of one hundred.

The decimal numbers appearing before titles are those which identify the headings being used in the analytic subject index of this journal. The Patent Office classification given in parentheses with each patent entry is outlined in the "Manual of Classification of Patents" which is obtainable from the Superintendent of Documents.

The opinions expressed are those of the individual reviewers.

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FRANK H. SLAYMAKER, *Stromberg Carlson Company, Rochester, New York*

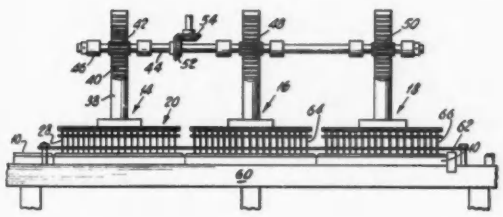
R. W. YOUNG, *C. G. Conn, Ltd., Elkhart, Indiana*

2,355,454

2.4 METHOD AND APPARATUS FOR THE PRODUCTION OF SOUND-ABSORBING MATERIALS

William I. Lucius, assignor to Johns-Manville Corporation.
August 8, 1944, 6 Claims (Cl. 164–125).

A method is described of integrally perforating acoustical tiles of the wood fiber type. Each tile is perforated successively by a series of punch presses having increasingly larger punches. The punches displace the fibers laterally, the successive operations being necessary to avoid crushing the material.—HJS



2,355,608

2.4 INSULATING AND ACOUSTICAL COVERING

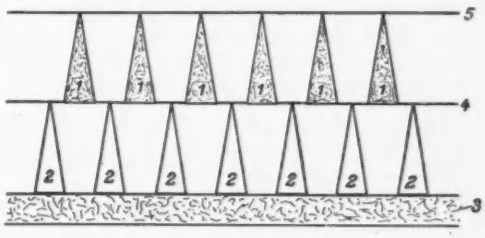
Philip J. Stieger.
August 15, 1944, 1 Claim (Cl. 154–44).

This patent describes a covering for acoustical materials which is formed of screen fabric and is intended to provide increased rigidity and a cleanable surface.—HJS

2,356,640

2.4 SOUND ABSORBING STRUCTURE

Hanns-Heinz Wolff; vested in the Alien Property Custodian.
August 22, 1944, 6 Claims (Cl. 20–4).

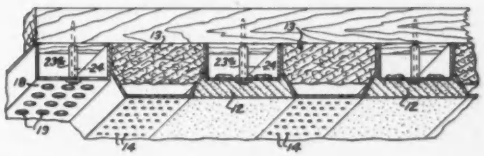


This construction, shown in section in the figure, comprises a multiplicity of pyramids or cones formed of sound absorbing material, the plane of their points forming the interior room surface. The patent specifies their being arranged in two or more staggered layers. A wire network is also provided for mounting the units.—HJS

2,357,560

2.4 ACOUSTICAL MATERIAL

Frank J. Taforo, Jr.
September 5, 1944, 10 Claims (Cl. 20–4).



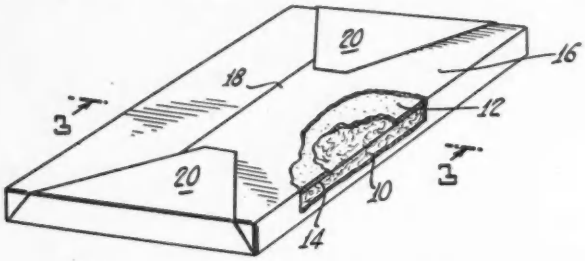
This method of acoustical treatment involves a single sheet of metal bent so as to form alternating strips or bands. One series provides the acoustical treatment in perforated metal pan form and the other series consists of troughs having large perforations in the bottom surface, into which plaster is applied flush with the acoustical surfaces. The system may be nailed to wood furring, as shown, or wired to steel channels.—HJS

2,357,115

2.4 SOUND-ABSORBING UNIT

William A. Jack, 3rd, and Andrew Menzak, Jr.
August 29, 1944, 5 Claims (Cl. 20–4).

The sound absorbing unit or pad includes in addition to the conventional porous material a diaphragm, as of relatively heavy asphalt saturated paper, adhered to the



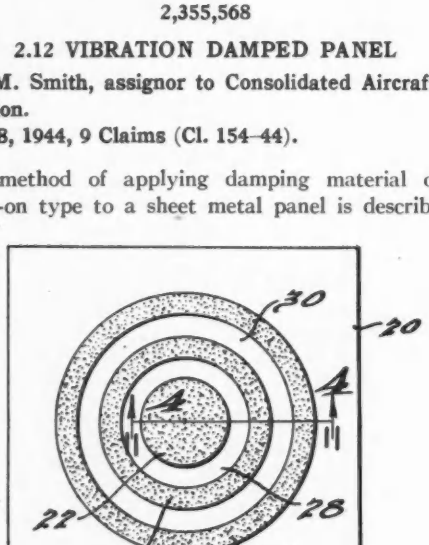
back side and intended to absorb sound of frequencies below 500 cycles. The entire unit is wrapped in a flexible sheet impervious to direct air flow but transparent to sound of all frequencies.—HJS

2,355,568

2.12 VIBRATION DAMPED PANEL

Frank M. Smith, assignor to Consolidated Aircraft Corporation.
August 8, 1944, 9 Claims (Cl. 154–44).

The method of applying damping material of the sprayed-on type to a sheet metal panel is described by



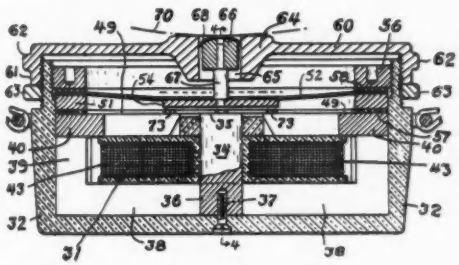
which a saving of at least 50 percent in the amount of damping material may be realized without loss of efficiency. The insulation is applied in a central spot and in surrounding rings or strips.—HJS

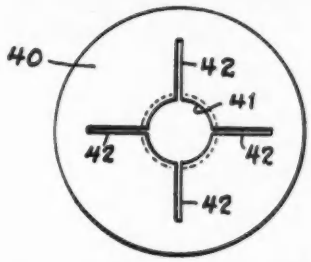
Re. 22,499

4.5 BONE CONDUCTION HEARING-AID

Hugo Lieber, assignor to Lieber Patents Corporation.
June 20, 1944, 9 Claims (Cl. 179–107).

In this bone conduction hearing aid unit the tensioned diaphragm **52** is resiliently mounted in case **32** and is



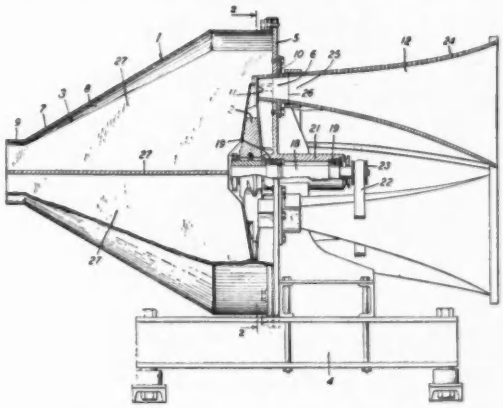


provided with a soft iron armature **54.** The magnetic field in the annular air gap formed by pieces **40** and **34** is energized by two L-shaped permanent magnets **39** and coil **31.** Vibration is imparted to the wearer by rod **67** and button **68,** the proportions being such that with normal pressure the button is depressed to a position conforming to the contour of raised portion **64.** In this position the operating gap between the armature surface and pole faces of the magnet core is about 3 mils or 0.003 in. Permanent bottoming is prevented by stops **73.**—LWS

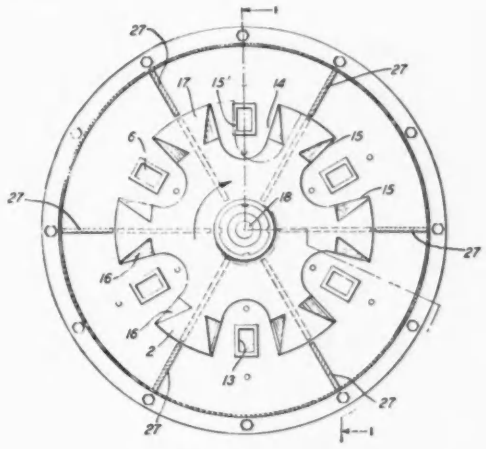
2,354,684

5.1 SIREN

Robert C. Jones, Horace T. O'Neil, and Edward C. Wente, assignors to Bell Telephone Laboratories, Incorporated.
August 1, 1944, 19 Claims (Cl. 116–147).



Claim 3 "A siren comprising a stator having therethrough a plurality of unobstructed apertures through which air passes in the generation of sound waves; means for supplying air to each of the stator apertures; a rotatable rotor mounted at one side of the stator between the means



for supplying air and the stator apertures having a portion, disposed in close proximity to the stator apertures and containing a plurality of rotor apertures, adapted to open and close the stator apertures during rotation of the rotor, each of the rotor apertures being at least about twice as wide in the direction of movement of the rotor relatively to the stator as each of the stator apertures and adjacent rotor apertures being spaced by a distance at least about twice the width of each of the stator apertures in the direction of movement of the rotor relatively to the stator; and, disposed at the side of the stator opposite the side at which the rotor is disposed, a plurality of acoustic horns, one for each of the stator apertures, each acoustic horn communicating with its stator aperture by a throat of substantially the same shape and area as the stator aperture, whereby is provided a substantially smooth and unimpeded path for air through the stator aperture and the horn."—RWY

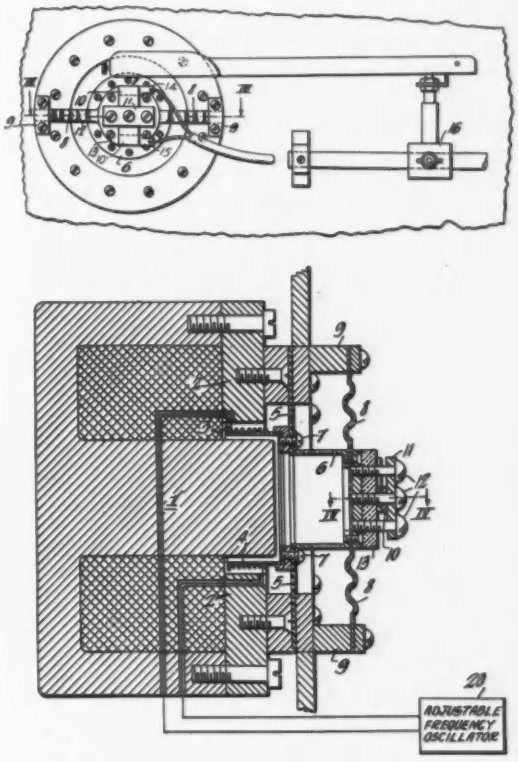
2,355,194

5.3 MECHANICAL IMPEDANCE MEASURING DEVICE

Alpha M. Wiggins, assignor to Radio Corporation of America.
August 8, 1944, 10 Claims (Cl. 73–51).

This is a device for measuring mechanical impedances of the order of 200 to several thousand mechanical ohms over the frequency range 500 to 5000 cycles per second. It is comprised of two identical reeds **10, 10′** clamped at their center and driven through mounting **6** supported by diaphragm **5** and strip **8** by coil **4.** The device to be measured, such as a phonograph pickup, is placed on the end of one of the reeds. Capacity pickup electrodes **14** and **15** are placed under the ends of the reeds. Electronic means are provided whereby the force on the unloaded reed may be determined and also the vector difference between the forces on each reed. The unknown impedance Z_x is given by the equation,

$$Z_x=[(F_2-F_1)/F_1][X_m-X_m^2/X_c].$$



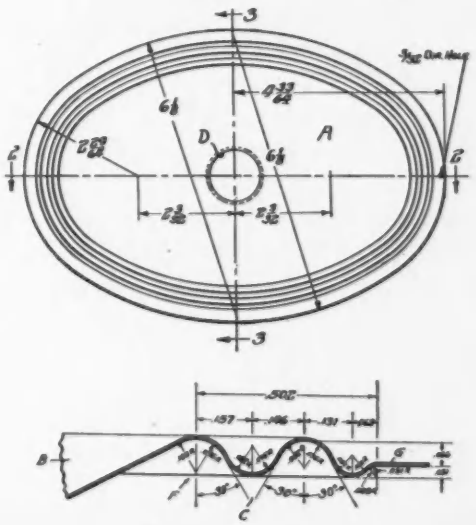
F_1 and F_2 are the forces on the unloaded and loaded reeds respectively, X_m is the reactance of the mass of either reed and X_c is the reactance of the compliance thereof.*—LWS

* See J. Acous. Soc. Am. 15, 50–53 (1943).

2,358,823

5.8 ELLIPTICAL CONE-SHAPED REPRODUCING DIAPHRAGM

Richard A. O'Connor and La Vern Edward Quinnell.
September 26, 1944, 4 claims (Cl. 181–31).

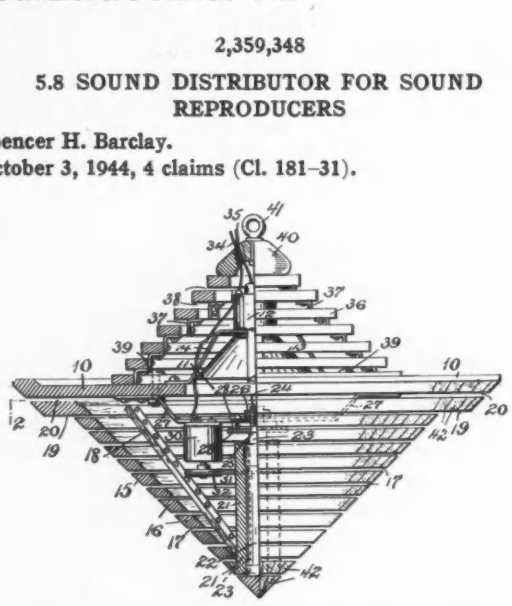


In working with loudspeakers having elliptical diaphragms the inventors have found that certain shapes of elliptical cones and the corrugated skiver surrounding the cones give more desirable frequency response characteristics than others. Although the patent specifications describe the shape of the cone as well as the skiver the claims are confined to the skiver.—FHS

2,359,348

5.8 SOUND DISTRIBUTOR FOR SOUND REPRODUCERS

Spencer H. Barclay.
October 3, 1944, 4 claims (Cl. 181–31).



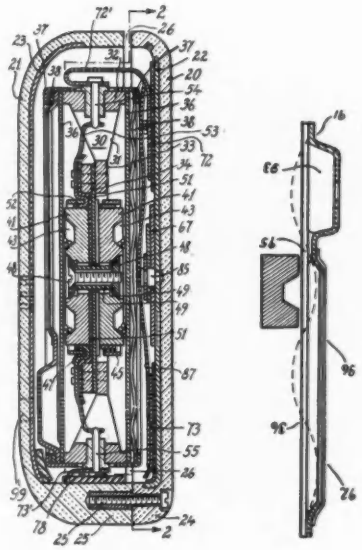
This distributor with its revolving rings **17** and colored mirrors **42** would fit very well into the juke box trade, but as an acoustical device it involves a discouraging number of misconceptions. The inventor states, "The whole structure has for its object increased resonance, improved distribution and a pleasing and attractive appearance," as though resonance in a loudspeaker were something to be desired rather than avoided. In referring to the cone shaped distributor and the slots between the rings he states, "This arrangement of the rings causes the sound waves to be directed laterally from the distributor and this is much more pronounced in large rooms or spaces when the distributor is rotated." He neglected to claim any acoustical advantage to be derived from the colored mirrors.—FHS

2,351,400

5.9 MICROPHONE

Richard W. Carlisle, assignor to Sonotone Corporation.
June 13, 1944, 14 claims (Cl. 179–107).

This is an elaborately detailed patent covering several features useful in hearing aid type microphones. To increase the sensitivity of the microphone two diaphragms **36** are included. The sound reaches these diaphragms through slots **26** around the periphery of the microphone case. The "mechano-electric energy translating element" is mounted within the case on flexible springs **72′** and **73′** which also serve as connectors to the carbon electrodes. This flexible support is intended to reduce mechanical

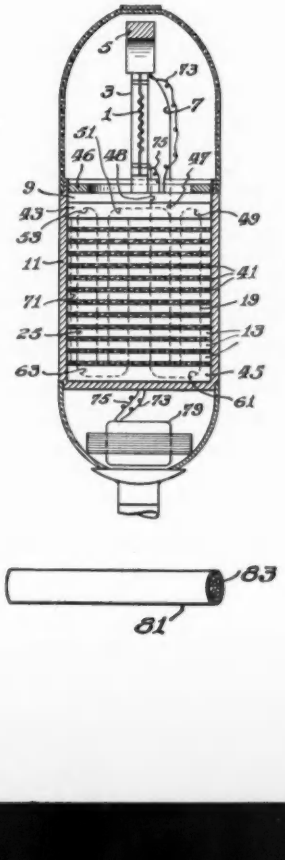


noise. The second figure shows the method used to increase the high frequency response of the microphone. The chamber **93** and the slot **95** are proportioned to resonate at the frequency corresponding to the mode of diaphragm vibration shown by the dashed line. This is accomplished without interfering with the fundamental mode of vibration.—FHS

2,352,305

5.9 MICROPHONE

Leslie J. Anderson, assignor to Radio Corporation of America.
June 27, 1944, 7 claims (Cl. 181–33).

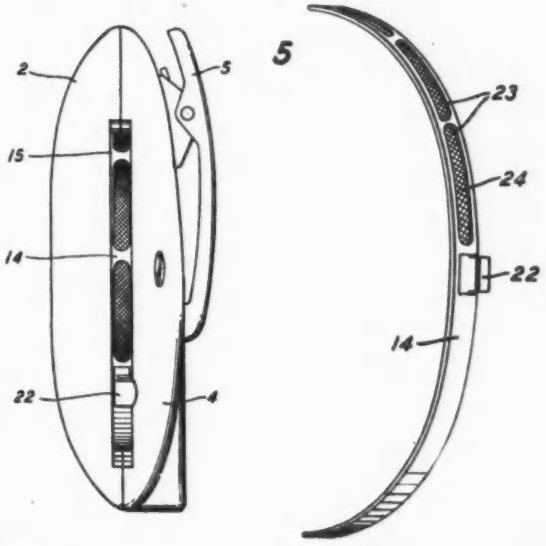


To make a ribbon microphone responsive to the sound pressure rather than the pressure gradient, microphones have been built in which a tube filled with some sort of damping material is used as a termination for the back side of the ribbon. This patent discloses two methods of constructing such a damped tube which permit quick assembly and insure an even distribution of the damping material. The first figure shows a section of one form of the microphone. A number of disks **13** having openings **19, 25** which can be aligned axially are assembled alternatingly with layers of silk **41**. The silk constitutes the acoustic resistance. An alternative scheme is shown in the second figure where the damping material **83,** is rolled up in a tube of paper **81.** This paper tube can then be inserted in the tubes formed by the openings in the disks when the silk is omitted, or inserted in tubes formed in a solid block of material.—FHS

2,358,099

5.9 TONE CONTROL FOR TRANSMITTERS

Robert E. Polk, assignor to Bell Telephone Laboratories, Incorporated.
September 12, 1944, 2 claims (Cl. 179–180).



The low frequency response of the microphone can be reduced by admitting sound to the back of the diaphragm as well as the front. The degree of low frequency cancellation can be controlled by changing the position of the shutter **14** in the slot **15.**—FHS

2,361,656

5.9 MICROPHONE DEVICE

Ernest William Rogers, assignor to Rediffusion Limited.
October 31, 1944, 17 Claims (Cl. 179–1).

The inventor of this device has combined two pairs of ribbon type velocity microphones in an arrangement shown in Figs. 1 and 2. The output signals from each pair of ribbon microphones are combined in the mixer shown in Fig. 3. The amplitude of the signal from each pair can be adjusted independently and the phase of either reversed. Although the inventor points out disadvantages in conventional velocity microphones, this elaborate arrangement does little that cannot be done by rotating a conventional ribbon microphone by hand. If, as the text of the patent states, the microphone "resembles, in action two single ribbons—centrally disposed but contained in relatively normal planes," the directional characteristics

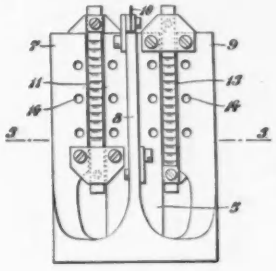


FIG. 1.

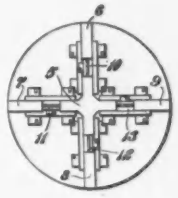


FIG. 2.

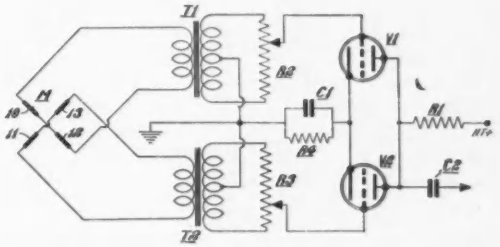


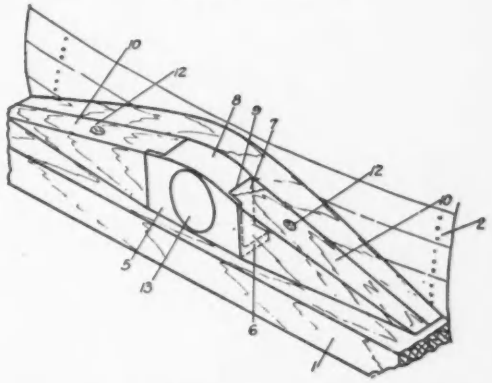
FIG. 3.

are always of the "Figure 8" type. The mixer circuits can only rotate the pattern and change the apparent microphone sensitivity.—FHS

2,360,923

5.10 SUBMARINE SIGNALING

Robert Longfellow Williams, assignor to Submarine Signal Company.
October 24, 1944, 3 Claims (Cl. 181–0.5).



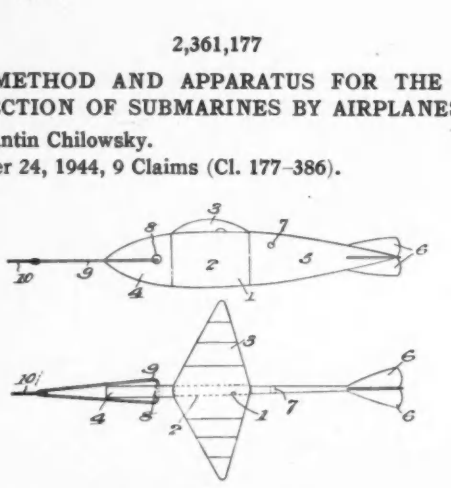
The shape of this case for a transducer for underwater signaling is such as to facilitate installation along the keel **1** of a wooden vessel in a manner to provide relatively smooth

flow of water, free of bubbles, past the transducer. The wooden fairing **10** is fitted around the transducer and behind the plate **5** in which the radiating face **13** is located.—RWY

2,361,177

5.10 METHOD AND APPARATUS FOR THE DETECTION OF SUBMARINES BY AIRPLANES

Constantin Chilowsky.
October 24, 1944, 9 Claims (Cl. 177–386).



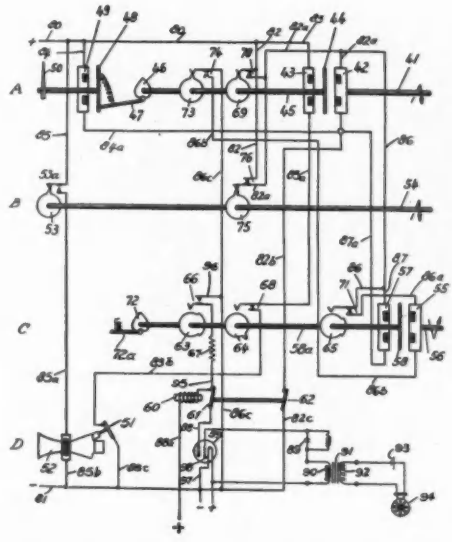
The problem of lowering a listening hydrophone into the water from an airplane is solved by utilizing a method previously disclosed by this inventor in U. S. Patent No. 1,829,474. "According to this method the airplane, in order to achieve contact with the ground, circles over the point selected for the contact while lowering a weight by a cable. This weight, instead of being thrown outward by centrifugal force, will stabilize itself at an appropriate cable length near the ground, on an inner circle of a much smaller diameter, both circles having the same vertical in their center. On the small circle the weight will possess a much lower linear speed than that of the airplane, which will permit making contact with the ground or with the water surface without danger to the object suspended from the cable." The underwater sound from the hydrophone may be carried to the airplane via a connecting cable or by radio. Means are disclosed for transmitting the orientation of the listening hydrophone. Several methods are mentioned for automatically maintaining the hydrophone at a given depth. A suitable aerodynamic form is given to the hydrophone as illustrated in the figures.—RWY

2,361,703

5.10 ECHO SOUNDING DEVICE

Peter Orlich, Gunther Negel and Hans Hartz; vested in the Alien Property Custodian.
October 31, 1944, 6 Claims (Cl. 177–386).

In echo sounding devices as commonly constructed, range scales must be used corresponding to the depth of water being measured. For deep water the interval between signals must be long in order to allow time for the reflected echo to return. To use the same cycle in shallow water results in a waste of time. "In the echo sounding device in accordance with the present invention, the above waste in waiting time intervals in the measuring cycles is avoided and quicker succession of soundings made possible by

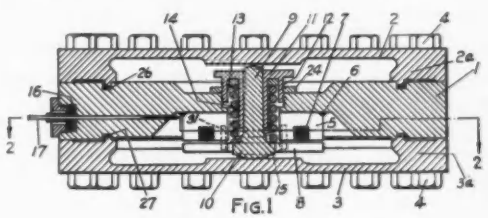


combining a detaining relay with the measuring apparatus, the relay initiating the return of the measuring mechanism to zero upon receipt of the echo while the pointer is maintained stationary in its indicating position. The operation of the system is such that at the instant, when the echo is received and thereby the measuring step of the measuring mechanism of one cycle is terminated, the measuring mechanism is detained in its position for such time interval as to allow the local indicator, which is connected to the measuring mechanism over a follower member, to follow the movement of the measuring mechanism. . . . The local indicator may be coupled with a transmission means for remotely controlling another indicator or other indicators at distant places. . . . The sound switch controlling the sound emission may be arranged in such a manner that it is actuated again immediately upon the return of the measuring apparatus to zero position. The conformance of the sequence of soundings to the elevation to be measured can thereby take place continuously or intermittently."—RWY

2,364,679

5.10 APPARATUS FOR SUBMARINE SIGNALING

Robert Longfellow Williams, assignor to Submarine Signal Company.
December 12, 1944, 4 Claims (Cl. 177–386).



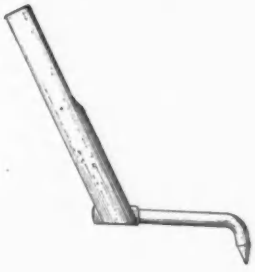
"The present invention is intended to provide a device for producing an underwater sound or noise of more or less continuous nature but containing a large frequency

spectrum while at the same time having a considerable energy content. Such a device has particular use as a sound source for tripping acoustically operated mines, particularly those of unknown frequency, as well as a sound source to be used for the calibration of binaural direction finding systems." The sound is radiated from the diaphragms **2** and **3** which are struck alternately by 9. The force of spring **14** is overcome by the attraction of armature **8** toward field **5** at a frequency double that of the alternating current flowing in coil **7**.—RWY

Des. 138,275

5.16 PHONOGRAPH STYLUS

Lloyd J. Andres, assignor to Permo, Incorporated.
July 11, 1944, 1 Claim (Cl. D26-14).

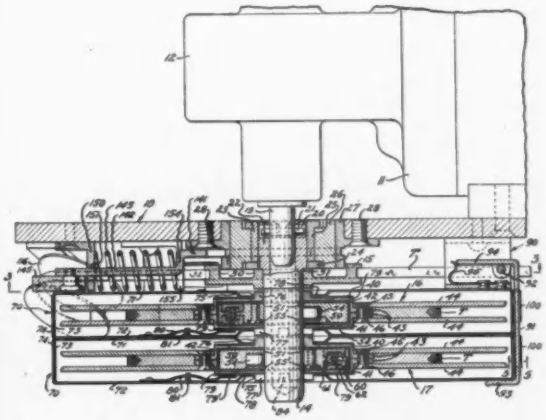


2,349,018

5.16 TAPE DRIVING SYSTEM FOR MAGNETIC SOUND RECORDING MACHINES AND THE LIKE

Homer G. Tasker, assignor to Herman S. Heller.
May 16, 1944, 4 Claims (Cl. 242–55).

In this driving system for a magnetic sound recording machine the tape driving pulley **15** and the take up and feed reels **16** and **17** are all disposed on the same shaft. The reels are driven through over-running clutches con-



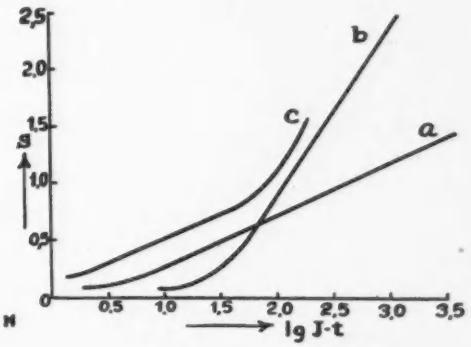
tained within the hubs of the reels. For the purpose of rewinding the clutch in one reel is arranged to drive clockwise and that in the other reel counterclockwise.—LWS

2,352,032

5.16 PRODUCTION OF SOUND RECORDS

Fritz Steube; vested in the Alien Property Custodian.
June 20, 1944, 3 Claims (Cl. 95–5).

According to this invention the advantages of both the usual straight line and toe methods of variable density sound-on-film recording are obtained by using a negative adapted to the normal positive film. Said negative film



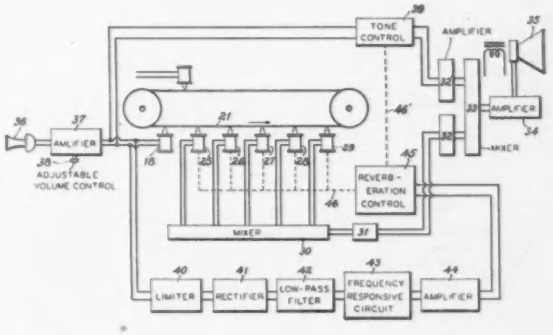
comprises at least two emulsions which produce a density curve according to **c** in the figure, the gamma of the rectilinear portion being the reciprocal of the positive gamma. In the figure **a** is the normal straight line density curve and **b** that used in the toe method.—LWS

2,354,176

5.16 AUTOMATIC REVERBERATION CONTROL

Alfred N. Goldsmith.
July 18, 1944, 20 Claims (Cl. 179–100.2).

This invention relates to a method of automatically controlling the amount of synthetic reverberation introduced into a program by means of a control device which is responsive to the tempo of the music. Thus for presto

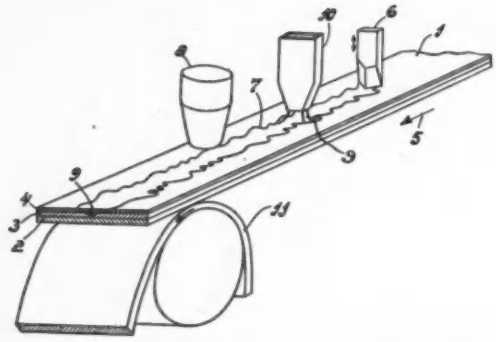


music a small amount of reverberation would be added and for largo music a larger amount would be added.—LWS

2,355,398

5.16 OSCILLATION RECORD

Pancras Schoonenberg, Jan Jesayas Hardenberg, and Cornelis Johannes Dippel, assignors, by mesne assignments, to Hartford National Bank and Trust Company.
August 8, 1944, 4 Claims (Cl. 106–37).

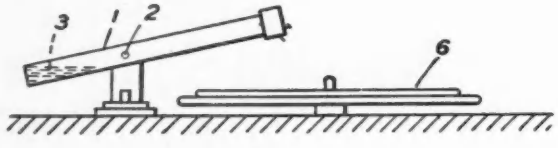


This patent relates to filling solutions for mechanically engraved variable width sound tracks intended for optical reproduction. Difficulty is encountered in printing such a record so it is proposed to fill the track with a material having the same index of refraction as the gelatin base **3** of the film. Several different solutions are disclosed which may be used in applicator **10** which lies between recording stylus **6** and printing light **8**.—LWS

2,356,467

5.16 GRAMOPHONE PICK-UP ARM

Robert Edgar Martin, assignor to International Standard Electric Corporation.
August 22, 1944, 8 Claims (Cl. 179–100.41).



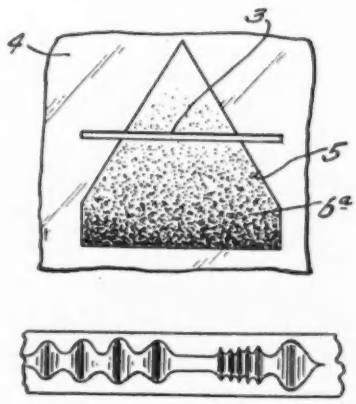
In this hollow tone arm a liquid counterweight such as mercury is used to maintain the pick-up in either an on-the-record or off-the-record position whichever is desired. —LWS

2,356,664

5.16 METHOD OF PRODUCING SOUND RECORDS ON FILM

Rolf Gorisch; vested in the Alien Property Custodian.
August 22, 1944, 6 Claims (Cl. 179–100.2).

"A method of producing a sound record of variable density on film in which at the same time the width of the record is varied, the steps of exposing successive areas of constant width of the film to a light source whose intensity varies in accordance with the variations in the sound vibrations and decreasing the width of the sound

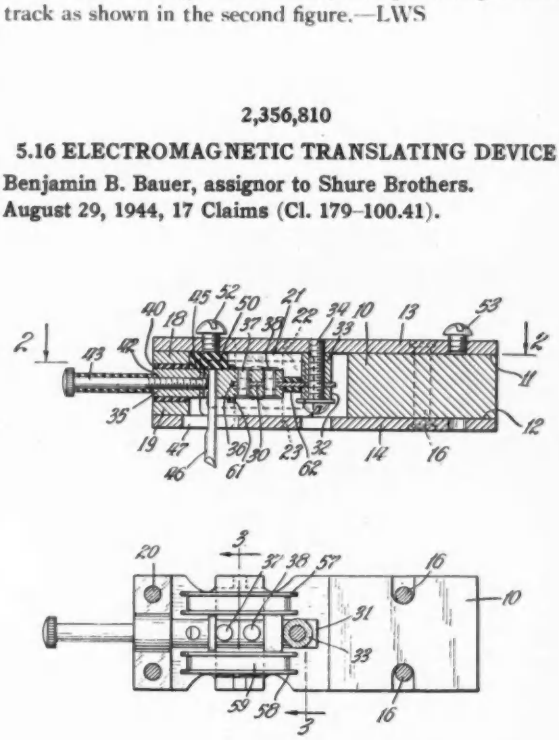


record in proportion to an increase of the transparency of the film." This is accomplished by moving a grey wedge **6a** combined with a triangular diaphragm **5** in front of a slit **3** which is imaged on the film, thus producing a sound track as shown in the second figure.—LWS

2,356,810

5.16 ELECTROMAGNETIC TRANSLATING DEVICE

Benjamin B. Bauer, assignor to Shure Brothers.
August 29, 1944, 17 Claims (Cl. 179–100.41).

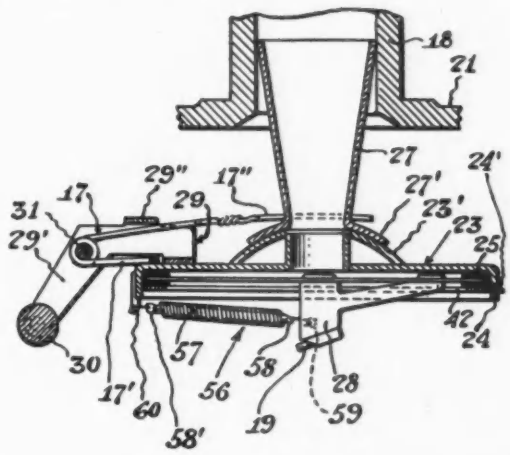


Simplicity of manufacture and freedom from adverse vibratory characteristics are the objectives of the electromagnetic translating device disclosed in this patent. Simple stampings are used for the pole pieces and armature. Part **30** is a T-shaped armature, of which **31** is the stem which serves as a torsion spring clamped between members **32** and **33**. The center section **30** also supports a drive rod **35** which is secured by rivets **37, 38.** The cutting stylus **46** is held in place by screw **43.** The heavily shaded portions are rubber bearings and damping blocks.—LWS

2,356,851

5.16 PHONOGRAPHIC TRANSLATING DEVICE

Charles Huenlich, assignor to Thomas A. Edison, Incorporated.
August 29, 1944, 5 Claims (Cl. 274–17).

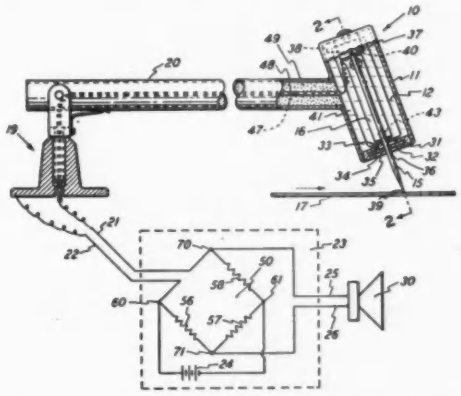


Improvement in frequency response and sensitivity of an acoustically actuated recorder, according to this disclosure, results from biasing the stylus and diaphragm against transverse forces which arise from cutting the groove. This is accomplished by means of spring **56** attached between the stylus stirrup **28** and the pin **60** welded to the casing. Wax-treated cord **58** threaded through the spring serves to damp its motion.—LWS

2,357,026

5.16 PHONOGRAPH

Serge Alexander Scherbatskoy.
August 29, 1944, 3 Claims (Cl. 179–100.4).

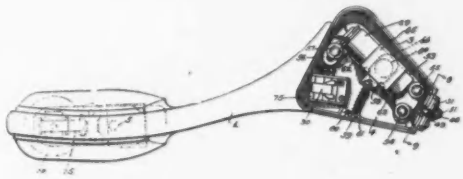


This phonograph pick-up utilizes the change in resistance between two terminals immersed in an electrolyte as the means for converting the undulations on a record into electrical signals. The pick-up is made one arm of a Wheatstone bridge and, according to the inventor, the usual vacuum tube amplifier may be eliminated.—LWS

2,359,808

5.16 PHONOGRAPH

Elmer O. Thompson, assignor to Philco Radio and Television Corporation.
October 10, 1944, 15 Claims (Cl. 179–100.41).

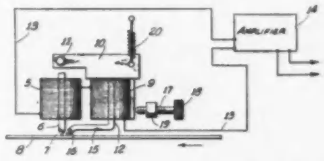


This patent relates to an improved phonograph reproducer of the electro-optical type, comprised of an adjustable light unit **29**, a modulator unit **3**, and a photo cell unit **30**. The lamp unit is also arranged to illuminate the record.—LWS

2,360,625

5.16 MAGNETIC RECORDING APPARATUS

Joseph B. Walker.
October 17, 1944, 3 Claims (Cl. 179–100.2).

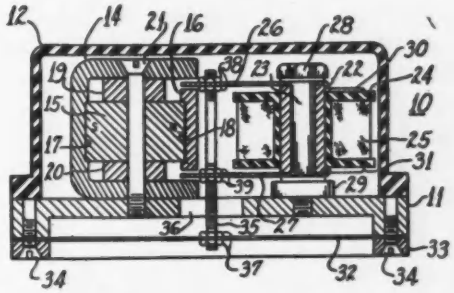


According to this invention better results may be obtained in magnetic tape recording by placing a second pole piece **16** of opposite polarity in close proximity to the main pole piece **7.** Said second pole piece is pivotably mounted and adjustable by means of screw **18.**—LWS

2,355,298

5.17 SOUND TRANSLATING DEVICE

Albert F. Horlacher, assignor to Automatic Electric Laboratories, Incorporated.
August 8, 1944, 7 claims (Cl. 175–339).



The sound-powered telephone described in this patent contains a double armature **26** and **27** instead of the conventional single one. The coil **25** is mounted on a

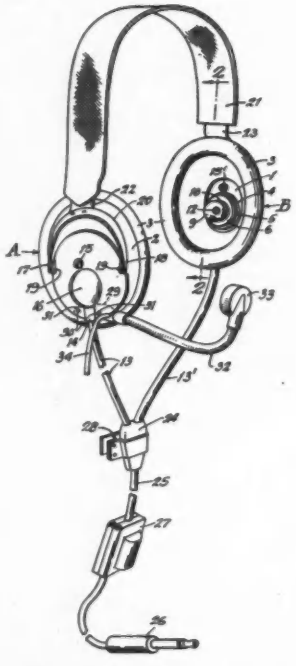
stationary core **22** and is not wound around the armature as is usually done in balanced armature units. With the armatures oriented symmetrically with respect to the pole piece **16** no flux flows through the armatures. Any vibration of the diaphragm **32** is transmitted to the armatures through the screw **35** and the motion of the armatures results in a varying flux flowing through the armatures and the core **22**.—FHS

2,353,070

5.17 HEADPHONE

Roy S. Pitkin, Jr.
July 4, 1944, 7 claims (Cl. 179–156).

The earphones described in this patent are modified insert type phones which are intended to seal the ear from external noise and to be more comfortable than conventional insert receivers. The cup **1** and the large rubber or synthetic rubber rim **3** completely enclose the wearer's ear, and serve the double function of preventing the rubber insert **9** from penetrating too far into the ear



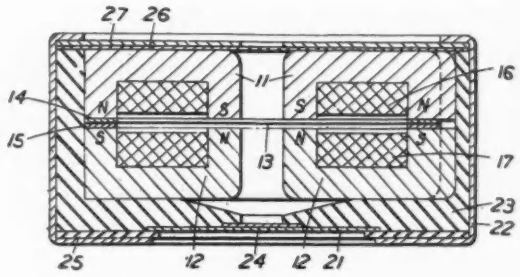
as well as preventing external noise from reaching the ear. Also shown is a microphone **33** mounted on a flexible support **32** which is fastened to one of the ear pieces. The claims, however, do not mention the microphone.—FHS

2,360,796

5.17 ELECTRO-ACOUSTIC DEVICE

James Samuel Paterson Roberton, assignor to International Standard Electric Corporation.
October 17, 1944, 3 Claims (Cl. 179–114).

The conventional sound-powered telephone embodies a balanced armature type unit. The device described in this

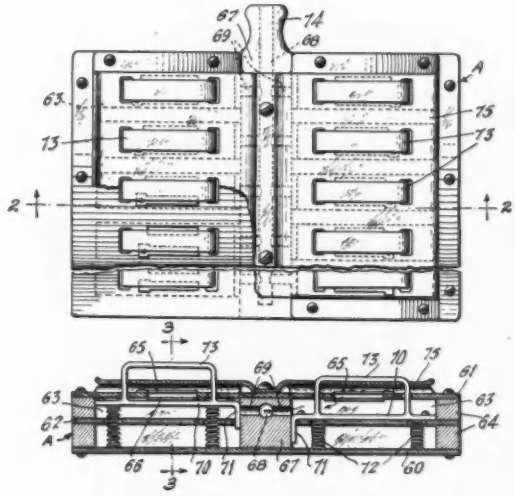


patent embodies what might be called a balanced diaphragm unit. The diaphragm **13** is mounted between the magnets **11** and **12**. These magnets are annular in shape and have a channel shaped section. The coils **16** and **17** are connected so current through the coils produces radial flux in the diaphragm. The diaphragm resonance is acoustically damped by the flow of air through the silk disk **24**.—FHS

2,348,830

6.1 HARMONICA

Finn H. Magnus.
May 16, 1944, 4 Claims (Cl. 84–377).



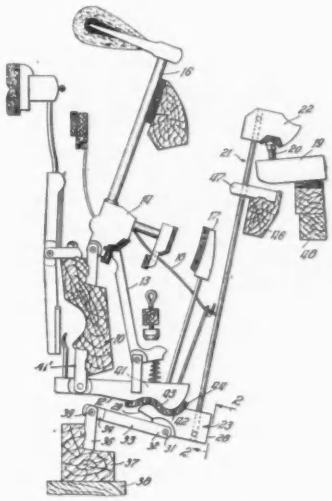
In this harmonica there is but a simple mouthpiece **74** for the wind tube **67** from which branch the passages **69** leading to each wind cell. Each set of reeds, consisting of a "blow" reed **65** and a "draw" reed **66**, is controlled by a valve **70**.—RWY

2,353,074

6.6 PIANO ACTION

Julian C. Potwin, assignor to Pratt, Read and Company.
July 4, 1944, 12 Claims (Cl. 84–240).

"A feature of this invention is found in the provision of a piano action having a pivoted whip [**12**] and abstract foot portion [**23**] arranged for striking engagement, but relatively formed so that a rocking action occurs there

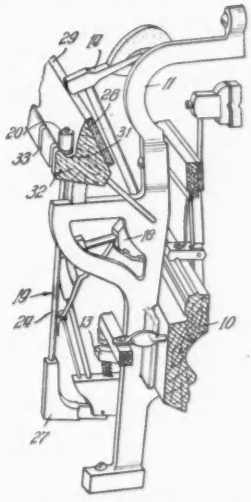


simultaneously with the pivotal lifting of the whip by the abstract. Any friction between these parts tending to restrict their free movement is thus practically eliminated."—RWY

2,361,573

6.6 PIANO ACTION

Charles Frederick Stein, assignor to Pratt, Read & Company, Incorporated.
October 31, 1944, 5 Claims (Cl. 84–240).



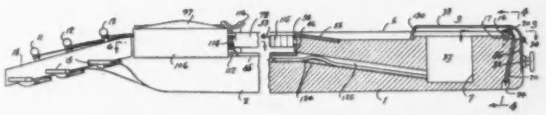
An object of this invention is to provide a drop-type action in which the free end **20** of the abstract is retained in a special groove **31** in the hammer rest rail while the action is being shipped or installed.—RWY

2,364,861

6.7 STRINGED MUSICAL INSTRUMENT

John W. McBride.
December 12, 1944, 18 Claims (Cl. 84–1.15).

In earlier patents 2,316,799 and 2,316,800 [see J. Acous. Soc. Am. **15**, 206–207 (1944)] this inventor has disclosed a

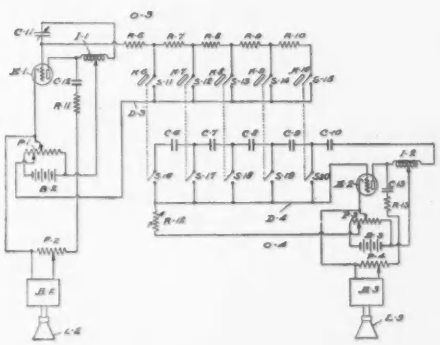


rod having helical-like crests so arranged that the effective length of the vibrating string of an instrument such as guitar is determined by rotating the rod to a definite angular location. "By the aid of the present invention, the tensioned string may be contacted at several spaced points by crests carried by the rod, so as to divide the string into a series of different lengths, each capable of being set into free vibration. . . . Agitation of all of the string sections may occur simultaneously if desired; and of course the vibrations can be obtained by rapid rotation or oscillation of the crested rod. All of the vibrations thus obtained are effectively transmitted by the aid of the string to affect the pickup **32.**" Improved means are also disclosed for locating the strings accurately parallel to the rods. A detent and a magnifier on the mechanism for rotating the rods assist in bringing them to the proper position for a given tone.—RWY

2,365,566

6.9 DUOPHONIC ELECTRICAL MUSICAL INSTRUMENT

Nicholas Langer, assignor to Central Commercial Company.
December 19, 1944, 7 Claims (Cl. 84–1.22).

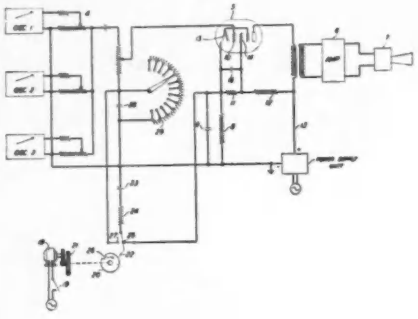


The frequencies of two oscillators which are designed for musical purposes are controlled from a single keyboard. If keys **K-6** and **K-9**, for example, are depressed simultaneously, there will issue from loudspeaker **L-2** a sound whose frequency is the lower of the two tones corresponding to the keys selected and from **L-3** will come the higher of the two tones. The trick is to employ chains of control elements such that only those elements below (or above) a given set of contacts are effective even though two or more keys are depressed.—RWY

2,354,699

6.9 SOUND GENERATOR

Emmett L. Owens, assignor to Bell Telephone Laboratories, Incorporated.
August 1, 1944, 2 Claims (Cl. 177–7).

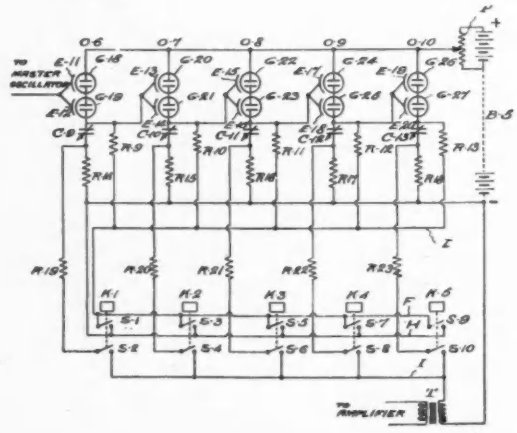


A percussive bell-like tone is produced by the switching sequence of this sound generator wherein the tone may be built up from oscillators such as **1, 2, 3.** The switching tube **5** is normally biased to cut off and condenser **23** is charged practically to the voltage across resistor **8.** As the motor driven cam **20** rotates, notch **26** allows switch follower **22** to move thereby closing the circuit at **27.** During an interval dependent upon the rate of rotation of the cam and the width of the notch, charge is transferred from condenser **23** to condenser **28.** This in effect momentarily reduces the bias on grid **10,** the tube becomes conducting and sound issues from loudspeaker **7.** This sound decays at a rate dependent upon the adjustment of resistor **29** through which **28** discharges.—RWY

2,365,567

6.9 MUSICAL INSTRUMENT

Nicholas Langer, assignor to Central Commercial Company.
December 19, 1944, 15 Claims (Cl. 84–1.19).

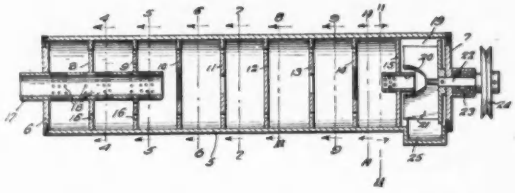


In certain previous electrical musical instruments in which all tone generators are operated continuously difficulty is said to be experienced from "cross-talk" between tone generating circuits. According to the present invention such cross-talk is minimized by starting the generators only when needed. For example, the set of relaxation oscillators **O-6** to **O-10** may be arranged to produce a set of tones spaced by octaves. An external master oscillator preferably of frequency equal to the highest frequency to be controlled may be used to stabilize the whole set. When key **K-4** is depressed the closing of contact **S-7** starts all oscillators, but only the output of **O-9** is connected by **S-8** to the output transformer **T.** Any cross-talk that does occur is not likely to be very noticeable since it is related by octaves to the tone being sounded. The use of two or more glow tubes in series increases the oscillating potentials available.—RWY

2,348,706

7.7 MUFFLER

Frederick K. Batchelor and Sidney E. Becker.
May 16, 1944, 2 Claims (Cl. 181–64).

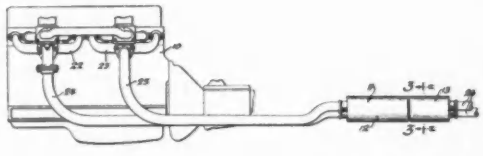


In an effort to reduce backpressure a scavenging fan is mounted on the end of this muffler. The fan is driven by external means.—CEN

2,356,782

7.7 INTERNAL-COMBUSTION ENGINE EXHAUST SYSTEM

Lloyd E. Muller, assignor to General Motors Corporation.
August 29, 1944, 9 Claims (Cl. 181–48).



In an attempt to reduce back pressure and still keep down the size of the muffler, this patent describes a multiple exhaust system. Two or more cylinders are connected to each exhaust line and these separate exhaust lines carry through a common silencer. They are interconnected inside the silencer however. It is claimed that this results in an exhaust system with less back pressure and in a more economical installation.—CEN

2,357,325

7.7 SILENCER FOR GAS HEATERS

George A. Guenther, assignor to Leon H. Ballou.
September 5, 1944, 3 Claims (Cl. 181–42).

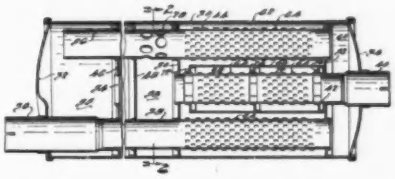
In this patent, silencing of a gas heater is accomplished by sound insulating couplings between sections of tubular conduits. A fibrous material such as felt serves as the sound absorber.—CEN

2,357,791

7.7 SILENCER

Walter H. Powers, assignor to Walker Manufacturing Company of Wisconsin.
September 5, 1944, 12 Claims (Cl. 181–54).

This patent describes a number of silencer constructions in which resonators are so located that the velocity head

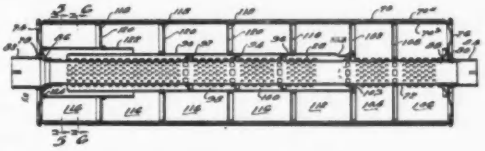


is used to drive part of the gas stream into the resonator. Certain manufacturing economics are also described.—CEN

2,357,792

7.7 SILENCER

Walter H. Powers, assignor to Walker Manufacturing Company of Wisconsin.
September 5, 1944, 6 Claims (Cl. 181–48).



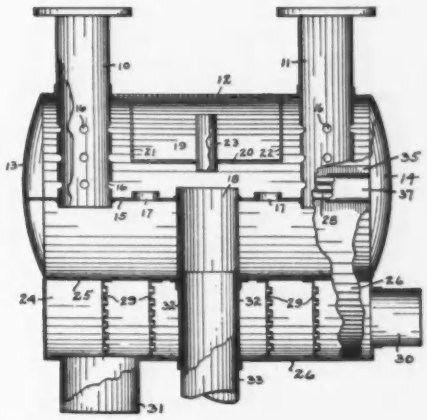
This patent describes a silencer construction in which an unusually long resonator tuning neck is realized by a parallel tube or a circumferential opening. These are shown as applying to mufflers of the straight through type.—CEN

2,361,133

7.7 MUFFLER

Verner E. Sprouse.
October 24, 1944, 6 Claims (Cl. 181–54).

In certain muffler applications, such as aircraft, it is desirable to extract heat from the exhaust gas as well as to

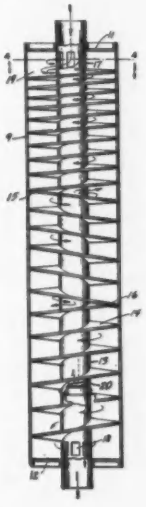


muffle the noise generated. In this patent the cylinder **12** comprises the muffler with the inlets at **10** and **11**, and the outlet at **33**. The heat exchanger box **24** has a number of perforated flanges **29** which aid in transferring the heat conducted and radiated from the muffler to the air which flows through the heater connections **30** and **31**.—CEN

2,359,365

7.7 MUFFLER

Morris Katcher.
October 3, 1944, 11 Claims (Cl. 181–67).



The inner tube of this muffler acts as a resonator so that successive direct and reflected pressure variations enter the spiral through openings **17**. This is claimed to silence the exhaust noise.—CEN

Index to Volume 16

How to Use This Index

This Index is of similar form to the Cumulative Index of this journal, published in November, 1939, and is composed of two main divisions: the Author Index and the Subject Index.

The Subject Index to Volume 16 of *The Journal of the Acoustical Society of America* lists the titles of all the papers, abstracts, and patents under twelve section headings as follows: 1, Acoustical Society of America; 2, Architectural Acoustics; 3, Books and Bibliographies; 4, Ear and Hearing; 5, Applied Acoustics. Instruments and Apparatus; 6, Musical Instruments and Music; 7, Noise; 8, Standards; 9, Speech and Singing; 10, Supersonics; 11, Waves and Vibrations; and 12, General, Unclassified. Each of these sections is further divided into a considerable number of decimally numbered subjects, which are listed below under the heading, "Classification of Subjects." Each subject is divided into four parts entitled Papers, Subtitles, Abstracts, and Patents. Under Papers will be found the original titles of all the papers appearing in the journal on that subject. Under Abstracts are listed the titles of the papers presented at meetings. Since a great amount of valuable material appears in the journal in papers whose titles cannot fully describe all the subjects which the papers cover, some subtitles of papers have been indexed under the heading Subtitles. When subtitles covering the material did not appear in the paper, they were written; the captions of some of the figures were also included under this heading. Thus, while the Subtitles portion of the index is informal, it is hoped that it will increase the probability of finding the desired information quickly. All patents appearing in the journal are listed under the heading Patents.

References on most subjects can be located immediately by a logical use of the Classification of Subjects below. In case the reference sought is of an unusual character such that there is uncertainty as to the subject under which it might have been classified, this can usually be found quite quickly by the process of eliminating the sections and subjects under which it is quite improbable that it might have been listed. In case of doubt, a title has often been listed under a number of subjects.

Obviously, the Author Index is more convenient than the Subject Index when one knows the name of the author of the paper in which he is interested.

The References to Contemporary Papers on Acoustics are identified in each issue by the same decimal numbers listed below, and may be consulted for references in other journals than our own. In Volume 16 these references will be found on pages 82, 129, 212, and 282.

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2.7 Reverberation, Theory and Calculation of (see also 2.3, 2.4, 2.8, 2.9, and 2.10)	None
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5.13 Public Address Systems and Sound Picture Installation	304
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Ballou, J. W. and J. C. Hubbard. Fixed path supersonic interferometer for liquids. **16**: 100(A)—1944

—— **and S. Silverman.** Young's modulus of elasticity of fibers and films by sound velocity measurements. **16**: 100(A), 113—1944

Bauer, B. B. Notes on distortion in phonograph reproduction caused by needle wear. **16**: 246—1945

Beranek, Leo L. Design of non-reverberant rooms for acoustic measurements. **16**: 98(T)—1944

Carlisle, R. W. and A. B. Mundel. Practical hearing aid measurements. **16**: 45, 99(A)—1944; Erratum. **16**: 125—1944

Carter, Howard A. Consideration of hearing aids and audiometers by the Council on Physical Medicine. **16**: 98(A)—1944; 203—1945

Chrzanowski, P. (see Cook, G. S.) **16**: 102(A)—1944

Cook, G. S. and P. Chrzanowski. Ear and closed coupler acoustic impedance. **16**: 102(A)—1944

Cook, Richard K. Sound wave fields within cavities. **16**: 102(A)—1944

Davis, Hallowell. Articulation tests for hearing aids. **16**: 98(T)—1944

Firestone, F. A. Book reviews. **16**: 81—1944

—— Current publications on acoustics. **16**: 80, 129—1944; 211, 282—1945

—— **and J. R. Frederick.** Supersonic reflectoscope; an instrument for inspecting the interior of metal parts by means of sound waves. **16**: 100(A)—1944

Fitzgerald, J. W. (see Klein, Elias) **16**: 100(T)—1944

Frederick, J. R. (see Firestone, F. A.) **16**: 100(A)—1944

Grossman, Frederick M. and Charles T. Molloy. Acoustic sound filtration and hearing aids. **16**: 52, 99(A)—1944

—— **and Charles T. Molloy.** Answer to Schier's letter to the editor. **16**: 207(L)—1945

Guild, Stacy R. Anatomical changes responsible for blast deafness and the prevention of such damage to the ear. **16**: 68, 98(T)—1944

Hales, Wayne B. Recording Lissajous figures. **16**: 137—1945

Hanson, Wilbur W. Baffle effect of the human body on the response of a hearing aid. **16**: 60, 102(A)—1944

Hartley, R. V. L. Production of inharmonic subfrequencies by a loudspeaker. **16**: 206—1945

Honigman, Esther. (see Molloy, Charles T.) **16**: 267—1945

Hubbard, J. C. (see Ballou, J. W.) **16**: 100(A)—1944

Jones, Arthur Taber. Singing flames. **16**: 254—1945

Jones, R. Clark. On the theory of the directional patterns of continuous source distributions on a plane surface. **16**: 147—1945

—— **and L. A. MacColl.** Theorem on directivity patterns. **16**: 100(A)—1944

Klein, Elias and J. W. Fitzgerald. Supersonic interferometer as an industrial tool for the study of liquids and solids. **16**: 100(T)—1944

Knoblaugh, Armand F. Clang tone of the pianoforte. **16**: 102(A)—1944

Labaw, L. W. Curved quartz crystals as supersonic generators. **16**: 100(A)—1944; 237—1945

—— (see Williams, A. O.) **16**: 231—1945

Lax, Melvin. Effect of radiation on the vibration of a circular diaphragm. **16**: 5—1944

LeBel, C. J. Pressure and field response of the ear in hearing aid performance determination. **16**: 63, 99(A)—1944

Leonard, R. W. Precision method for the determination of the velocity of sound in air. **16**: 101(A)—1944

Lindsay, R. B. (see Smyth, J. B.) **16**: 20—1944

Lowy, Karl. Evidence for the existence of peripheral auditory masking. **16**: 98(A)—1944

—— Some experimental evidence for peripheral auditory masking. **16**: 197—1945; Erratum, 279—1945

MacColl, L. A. (see Jones, R. Clark) **16**: 101(A)—1944

McGinnis, C. S. and R. Pepper. Intonation of the Boehm clarinet. **16**: 188—1945

Mark, H. High frequency treatment and investigation of organic high polymers. **16**: 100(T)—1944

—— Some applications of ultrasonics in high-polymer research. **16**: 183—1945

Matta, K. and M. Mohktar. Velocity of sound in vapors. **16**: 120—1944

Meeker, Willard F. (see Olney, Benjamin) **16**: 102(A)—1944; 172—1945

—— **and Frank H. Slaymaker.** Wide-range adjustable acoustic impedance. **16**: 102(A)—1944; 178—1945

Miles, John. Reflection of sound due to a change in cross section of a circular tube. **16**: 14—1944

Mobley, M. R. Army aural rehabilitation program. **16**: 98(T)—1944

Mohktar, M. (see Matta, K.) **16**: 120—1944

Molloy, Charles T. Propagation of sound in lined ducts. **16**: 31, 102(A)—1944

—— (see Grossman, Frederick M.) **16**: 52, 99(A)—1944

—— (see Grossman, Frederick M.) **16**: 207(L)—1945

—— **and Esther Honigman.** Attenuation of sound in lined ducts. **16**: 267—1945

Morse, Philip M. Book review. **16**: 80—1944

Mundel, A. B. (see Carlisle, R. W.) **16**: 45, 99(A), 125—1944

Nichols, Rudolph. Methods of testing the electrical and acoustical properties of hearing aids. **16**: 98(T)—1944

Obert, Leonard. Application of acoustical methods in mining problems. **16**: 100(T)—1944

Olney, Benjamin, Frank H. Slaymaker, and Willard F. Meeker. Dipole microphone. **16**: 102(A)—1944; 172—1945

Olson, Harry F. Action of a direct radiator loudspeaker with a non-linear cone suspension system. **16:** 1, 100(A)—1944

Pauls, Miriam D. Role of the college and university hearing clinic. **16:** 98(A)—1944
Pepinsky, Abe. Book review. **16:** 129—1944
Pepper, R. (see McGinnis, C. S.) **16:** 188—1945
Pielemeier, W. H. Kneser's sound absorption nomogram and other charts. **16:** 273—1945

Roseberry, H. Hewell and W. Conley Smith. Rayleigh disk as a laboratory instrument. **16:** 123—1944

Sabine, Paul E. Acoustical amplification by hearing aids. **16:** 38, 99(A)—1944
Saunders, F. A. Analyses of tones of wind instruments and of resonating strings. **16:** 101(A)—1944
Schier, Mayer B. A. Letter to the Editor. **16:** 126—1944
Shilling, C. W. Acoustical trauma as encountered in submarine duty. **16:** 98(T)—1944
Siegel, Sidney. Measurements of elastic and dissipative properties of solids by supersonic methods. **16:** 99(A)—1944
—— Review of supersonic methods for measuring elastic and dissipative properties of solids. **16:** 26—1944
Silverman, S. R. Clinical comparison of air- and bone-conduction hearing aids in cases of conductive impairment of hearing. **16:** 108—1944
—— (see Ballou, J. W.) **16:** 100(A), 113—1944
Sivian, L. J. Introductory remarks. **16:** 99(T)—1944
Slaymaker, Frank H. (see Meeker, Willard F.) **16:** 102(A)—1944; 178—1945
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Smith, W. Conley. (see Roseberry, H. Hewell) **16:** 123—1944
Smyth, J. B. and R. B. Lindsay. Supersonic transmission at oblique incidence through a solid plate in water. **16:** 20—1944
Steinberg, John C. Physics of hearing measurements. **16:** 98(T)—1944

Thiessen, G. J. R-C filter circuits. **16:** 275—1945
Truex, Edward H., Jr. Rehabilitation service for the hard of hearing at Deshon General Hospital, Butler, Pennsylvania. **16:** 71—1944

Watson, Norman A. Air- and bone-conduction audiotesting assembly. **16:** 98(A)—1944; 194—1945
Williams, A. O. and L. Labaw. Acoustic intensity distribution from a "piston" source. **16:** 231—1945

Young, Robert W. Review of acoustical patents. **16:** 84, 131—1944; 214, 285—1945
—— Some problems for postwar musical acoustics. **16:** 101(A), 103—1944

Zener, Clarence. Anelasticity of metals. **16:** 100(A)—1944

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1.5 Meetings

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New members. **16**: 76, 127—1944; 209, 280—1945
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2.8 Reverberation Measuring Instruments

PATENT

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2.9 Sound Transmission, Theory and Methods of Measurement of

PAPER

Attenuation of sound in lined ducts. Charles T. Molloy and Esther Honigman. **16**: 267—1945
Propagation of sound in lined ducts. Charles T. Molloy. **16**: 31—1944

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Speech reading—Jena method. Anna M. Bunger. **16**: 211—1945
Table of the Bessel functions $J_0(Z)$ and $J_1(Z)$ for complex arguments. Prepared by the Mathematical Tables Project of the Work Projects Administration of the Federal Works Agency. **16**: 81—1944
Table of circular and hyperbolic tangents and cotangents for radian arguments. Prepared by the Mathematical Tables Project of the Work Projects Administration of the Federal Works Agency. **16**: 81—1944
Table of reciprocals of the integers from 100,000 through 200,009. Prepared by the Mathematical Tables Project of the Work Projects Administration of the Federal Works Agency. **16**: 81—1944
Tables of Lagrangian interpolation coefficients. Prepared by the Mathematical Tables Project of the Work Projects Administration of the Federal Works Agency. **16**: 81—1944
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Transients in linear systems. Volume I. Murray F. Gardner and John L. Barnes. **16**: 80—1944

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Rehabilitation service for the hard of hearing at Deshon General Hospital, Butler, Pennsylvania. Edward H. Truex, Jr. **16**: 71—1944

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Acoustical trauma as encountered in submarine duty. C. W. Shilling. **16:** 98—1944
Anatomical changes responsible for blast deafness and the prevention of such damage to the ear. Stacey R. Guild, M.D. **16:** 98—1944
Army aural rehabilitation program. M. R. Mobley. **16:** 98—1944
Role of the college and university hearing clinic. Miriam D. Pauls. **16:** 98—1944
Speech reading—Jena method. Anna M. Bunger. **16:** 211—1945

SUBTITLE
Northwestern symposium on hearing aids and residual hearing. **16:** 76—1944

4.5 Instruments Relating to Hearing

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Acoustic sound filtration and hearing aids. Frederick M. Grossman and Charles T. Molloy. **16:** 52—1944
Acoustical amplification by hearing aids. Paul E. Sabine. **16:** 38—1944
Air- and bone-conduction audio testing assembly. Norman A. Watson. **16:** 194—1945
Answer to Schier's letter to the editor. Frederick M. Grossman and Charles T. Molloy. **16:** 207—1945
Baffle effect of the human body on the response of a hearing aid. Wilbur W. Hanson. **16:** 60—1944
Clinical comparison of air and bone conduction hearing aids in cases of conductive impairment of hearing. S. R. Silverman. **16:** 108—1944
Consideration of hearing aids and audiometers by the council on physical medicine. Howard A. Carter. **16:** 203—1945
Erratum: Practical hearing aid measurements. R. W. Carlisle and A. B. Mundel. **16:** 125—1944
Letter to the editor. Mayer B. A. Schier. **16:** 126—1944
Practical hearing aid measurements. R. W. Carlisle and A. B. Mundel. **16:** 45—1944
Pressure and field response of the ear in hearing aid performance determination. C. J. LeBel. **16:** 63—1944

ABSTRACTS
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Acoustic sound filtration and hearing aids. Frederick M. Grossman and Charles T. Molloy. **16:** 99—1944
Articulation tests for hearing aids. Hallowell Davis. **16:** 98—1944
Baffle effect of the human body on the response of a hearing aid. Wilbur W. Hanson. **16:** 102—1944
Consideration of hearing aids and audiometers by the council on physical therapy. Howard A. Carter. **16:** 98—1944
Methods of testing the electrical and acoustical properties of hearing aids. Rudolph Nichols. **16:** 98—1944
Practical hearing aid measurements. R. W. Carlisle and A. B. Mundel. **16:** 99—1944
Pressure and field response of the ear in hearing aid performance determination. C. J. LeBel. **16:** 99—1944

PATENTS
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Bone conduction receiver. **16:** 85—1944
Earphone. **16:** 216—1945
Earphone support and silencer cup. **16:** 84—1944
Portable microphone and amplifier. **16:** 85—1944

4.6 Loudness. Threshold Determinations

PAPER
Air- and bone-conduction audio testing assembly. Norman A. Watson. **16:** 194—1945
Pressure and field response of the ear in hearing aid performance determination. C. J. LeBel. **16:** 63—1944

ABSTRACT
Air- and bone-conduction audio-testing assembly. Norman A. Watson. **16:** 98—1944

4.7 Masking

PAPER
Some experimental evidence for peripheral auditory masking. Karl Lowy. **16:** 197—1945

ABSTRACT
Evidence for the existence of peripheral auditory masking. Karl Lowy. **16:** 98—1944

4.13 Ear Acoustical Impedance

ABSTRACT
Ear and closed coupler acoustic impedance. G. S. Cook and P. Chrzanowski. **16:** 102—1944

5. Applied Acoustics. Instruments and Apparatus

5.1 General, Unclassified

PAPER
Recording Lissajous figures. Wayne B. Hales. **16:** 137—1945
Singing flames. Arthur Taber Jones. **16:** 254—1945

ABSTRACT
Application of acoustical methods to mining problems. Leonard Obert. **16:** 100—1944

PATENTS
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Chime unit. **16:** 85—1944
Horn control system. **16:** 217—1945
Siren. **16:** 286—1945

5.3 Acoustical Impedance Measurement (see also 11.4)

PAPER
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ABSTRACT
Ear and closed coupler acoustic impedance. G. S. Cook and P. Chrzanowski. **16:** 102—1944
Wide-range adjustable acoustic impedance. Willard F. Meeker and Frank H. Slaymaker. **16:** 102—1944

PATENT
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5.4 Analyzers and Filters. Acoustic Filters. Oscillographs

PAPER

Acoustic sound filtration and hearing aids. Frederick M. Grossman and Charles T. Molloy. **16:** 52—1944
R-C filter circuits. G. J. Thiessen. **16:** 275—1945

PATENTS

Mechanical wave filter. **16:** 86—1944
Method and apparatus for sound analysis. **16:** 86—1944
Wave filter. **16:** 86—1944
Wave transmission network. **16:** 217—1945

5.7 Frequency Standards. Frequency Measuring and Recording Instruments. Hearing Instruments (see 4.5)

PAPER

Recording Lissajous figures. Wayne B. Hales. **16:** 137—1945

PATENTS

Rate control for tuning fork oscillators. **16:** 217—1945

5.8 Loudspeakers. Horns (see also 5.13 and 5.17)

PAPER

Action of a direct radiator loudspeaker with a non-linear cone suspension system. Harry F. Olson. **16:** 1—1944
Production of inharmonic subfrequencies by a loudspeaker. R. V. L. Hartley. **16:** 206—1945

PATENTS

Electric horn. **16:** 217—1945
Elliptical cone-shaped reproducing diaphragm. **16:** 287—1945
Loudspeaker. **16:** 217—1945
Sound distributor for sound reproducers. **16:** 288—1945.
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5.9 Microphones. Vibration Microphones. Microphone Calibration Equipment

PAPER

Dipole microphone. Benjamin Olney, Frank H. Slaymaker, and Willard F. Meeker. **16:** 172—1945

ABSTRACT

Design of non-reverberant rooms for acoustic measurements. Leo L. Beranek. **16:** 98—1944
Dipole microphone. Benjamin Olney, Frank H. Slaymaker and Willard F. Meeker. **16:** 102—1944

PATENTS

Carbon microphone. **16:** 87—1944
Electromagnetic oscillating device with freely oscillating armature. **16:** 86—1944
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5.10 Navigational Instruments. Depth and Altitude Measuring Instruments. Geophysical Prospecting. Underwater Sound. Submarine Detectors

ABSTRACT

Application of acoustical methods to mining problems. Leonard Obert. **16:** 100—1944

PATENTS

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Echo sounding apparatus. **16:** 87—1944
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Sonic depth indicator. **16:** 220—1945
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5.13 Public Address Systems and Sound Picture Installations

PATENTS

Method of recording and reproducing stereophonic sound vibrations. **16:** 87—1944
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5.14 Rayleigh Disks. Reverberation Measuring Instruments (see 2.8)

PAPER

Rayleigh disk as a laboratory instrument. H. Hewell Roseberry and W. Conley Smith. **16:** 123—1944

5.16 Sound Recording and Reproducing. Speech Instruments. Supersonic Instruments (see 10.3)

PAPER

Notes on distortion in phonograph reproduction due to needle wear. B. B. Bauer. **16:** 246—1945

PATENTS

Apparatus for operating phonographs and processing records therefor. **16:** 88—1944
Automatic reverberation control. **16:** 291–1945

Combination oscillator coil and erasing head for magnetic recorders. **16:** 225—1945
Copying sound events taken in amplitude records. **16:** 89—1944
Electromagnetic translating device. **16:** 292—1945
Electron discharge oscillation generator. **16:** 88—1944
Gramophone pick-up arm. **16:** 292—1945
Laminated sound record. **16:** 226—1945
Magnetic recorder. **16:** 225—1945
Magnetic recording apparatus. **16:** 292–1945
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Magnetic recording machine. **16:** 132—1944
Magnetic sound recording and reproducing. **16:** 228—1945
Material for records. **16:** 89—1944
Method and means of magnetic recording. **16:** 224—1945
Method of and means for energizing magnetic recorder heads. **16:** 226—1945
Method of and means for controlling high frequency voltage in magnetic recorder heads. **16:** 226—1945
Method of and means for neutralizing inductive disturbances in magnetic reproducers. **16:** 225—1945
Method of making phonograph record stampers. **16:** 227—1945
Method of producing sound band matrices. **16:** 227—1945
Method of producing sound records on film. **16:** 292—1945
Multiple-speed phonograph turntable. **16:** 133—1944
Oscillation record. **16:** 292—1945
Phase modulation recording and reproducing system. **16:** 134—1944
Phonograph. **16:** 293—1945
Phonographic translating device. **16:** 293—1945
Phonograph pick-up. **16:** 89—1944
Phonograph pick-up apparatus. **16:** 88—1944
Phonograph record and method of making. **16:** 133—1944
Phonograph stylus. **16:** 291—1945
Process for recording by direct lithographic printing, sounds impinging on microphones or the like. **16:** 89—1944
Production of sound records. **16:** 291—1945
Recording and reproducing sound. **16:** 133—1944
Recording and reproducing of vibrations. **16:** 224—1945
Sound record and method of making. **16:** 224—1945
Sound recording apparatus. **16:** 88—1944, 224—1945
Sound recording device. **16:** 88—1944
Sound recording and reproducing apparatus. **16:** 226—1945
Sound recording with supersonic modulator. **16:** 133—1944
Sound recording system. **16:** 134—1944
Sound reproducer. **16:** 227—1945
Tape driving system for magnetic sound recording machines and the like. **16:** 291—1945
Sound translating device. **16:** 293—1945
Vibration translating device. **16:** 223—1945

5.17 Telephones, Telephone Receivers

PATENTS

Acoustic device. **16:** 228—1945
Ear shield and acoustic transmitting device. **16:** 89—1944
Headphone. **16:** 294—1945
Electro-acoustic device. **16:** 294—1945
Variable baffle for translating devices. **16:** 90—1944

5.19 Tuning Forks

PATENTS

Phonograph. **16:** 228—1945

5.21 Vibration Devices (see also 5.9)

PATENTS

Method of and apparatus for measuring mechanical vibrations. **16:** 228—1945
Torsional vibration damper. **16:** 90—1944
Vibration amplitude and center of oscillation indicator. **16:** 90—1944

6. Musical Instruments and Music

6.1 General, Unclassified

PAPER

Some problems for postwar musical acoustics. Robert W. Young. **16:** 103—1944

ABSTRACT

Physics of music. Alexander Wood. **16:** 129—1944
Some problems for post-war musical acoustics. Robert W. Young. **16:** 101—1944

PATENTS

Chromatic harmonica. **16:** 90—1944
Harmonica. **16:** 90—1944; 294—1945
Keyboard for accordions. **16:** 91—1944
Musical device. **16:** 134—1944
Musical instrument. **16:** 228—1945

6.3 Brass

ABSTRACT

Analysis of tones of wind instruments and of resonating strings. F. A. Saunders. **16:** 101—1944

PATENTS

Foot operatable attachment for valved wind instruments. **16:** 229—1945

6.4 Drums and Traps

PATENTS

Musical instruction device. **16:** 91—1944
Musical instrument. **16:** 91—1944
Musical instrument. **16:** 91—1944
Xylophone. **16:** 19—1944, 229—1945

6.5 Organs

PATENTS

Multiple magnetic valve for organs. **16:** 92—1944

6.6 Pianos

ABSTRACT

Clang tone of the pianoforte. Armand F. Knoblaugh. **16:** 102—1944

PATENTS

Escapement action for grand pianos. **16:** 92—1944
Operating means for piano actions. **16:** 92—1944
Piano action. **16:** 294, 295—1945
Piano pin block. **16:** 92—1944

6.7 Violin Family

ABSTRACT

Analysis of tones of wind instruments and of resonating strings. F. A. Saunders. **16:** 101—1944

PATENTS

Multistringed musical instrument. **16:** 134—1944
Process and apparatus for making gut strings. **16:** 93—1944
Stringed musical instrument. **16:** 93—1944; 295—1945
Tuning head for stringed instruments. **16:** 229—1945

6.8 Wood Winds

PAPER

Intonation of the Boehm clarinet. C. S. McGinnis and R. Pepper. **16:** 188—1945

ABSTRACT

Analysis of tones of wind instruments and of resonating strings. F. A. Saunders. **16:** 101—1944

PATENTS

Reed for musical instruments. **16:** 93—1944

6.9 Electronic Musical Instruments

PATENTS

Duophonic electrical musical instrument. **16:** 295—1945
Electric instrument. **16:** 94—1944
Electrical musical instrument. **16:** 93, 94—1944, 229—1945
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Sound generator. **16:** 296—1945

7. Noise

7.6 Noise in Buildings

PATENTS

Acoustic attenuator for air impellers. **16:** 95—1944
Door. **16:** 95—1944
Method and means for acoustical treatment. **16:** 95—1944

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PATENTS

Internal combustion engine exhaust system. **16:** 97—1944; 296—1945
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Suction muffler for airplanes, automobiles, and the like. **16:** 97—1944
Water cooled silencer. **16:** 96—1944

8. Standards

9. Speech and Singing

9.1 General, Unclassified

ABSTRACT

Speech reading—Jena method. Anna M. Bunger. **16:** 211—1945

10. Supersonics (Ultrasonics)

10.3 Supersonic Instruments

PAPER

Curved quartz crystals as supersonic generators. L. W. Labaw. **16:** 237—1945

ABSTRACT

Curved quartz crystals as supersonic generators. L. W. Labaw. **16:** 100—1944
Fixed path supersonic interferometer for liquids. J. W. Ballou and J. C. Hubbard. **16:** 100—1944
Supersonic interferometer as an industrial tool for the study of liquids and solids. Elias Klein and J. W. Fitzgerald. **16:** 100—1944
Supersonic reflectoscope; an instrument for inspecting the interior of metal parts by means of sound waves. F. A. Firestone and J. R. Frederick. **16:** 100—1944

10.4 Gases, Supersonic Velocities, Dispersion, and Absorption (see also 11.3)

PAPER

Kneser's sound absorption nomogram and other charts. W. H. Pielemeier. **16:** 273—1945
Velocity of sound in vapors. K. Matta and M. Mokhtar. **16:** 120—1944

10.5 Liquids, Supersonic Velocities, Dispersion, and Absorption

PAPER

Supersonic transmission at oblique incidence through a solid plate in water. J. B. Smyth and R. B. Lindsay, **16:** 20—1944

ABSTRACT

Fixed path supersonic interferometer for liquids. J. W. Ballou and J. C. Hubbard. **16:** 100—1944

10.6 Solids, Supersonic Velocities, Dispersion, and Absorption

PAPER

Review of supersonic methods for measuring elastic and dissipative properties of solids. Sidney Siegel. **16:** 26—1944

Supersonic transmission at oblique incidence through a solid plate in water. J. B. Smyth and R. B. Lindsay. **16:** 20—1944

ABSTRACT

Measurements of elastic and dissipative properties of solids by supersonic methods. Sidney Siegel. **16:** 99—1944

10.8 Chemical Effects of Supersonic Waves

PAPER

Some applications of ultrasonics in high-polymer research. H. Mark. **16:** 183—1945

ABSTRACT

High frequency treatment and investigation of organic high polymers. H. Mark. **16:** 100—1944

11. Waves and Vibrations

11.3 Propagation of Sound, Absorption during Propagation. Velocity of Sound. (See also 10.4)

PAPER

Kneser's sound absorption nomogram and other charts. W. H. Pielemeier. **16:** 273—1945

Young's modulus of elasticity of fibers and films by sound velocity measurements. J. W. Ballou and S. Silverman. **16:** 113—1944

ABSTRACT

Anelasticity of metals. Clarence Zener. **16:** 100—1944

Precision method for the determination of the velocity of sound in air. R. W. Leonard. **16:** 101—1944

Young's modulus of elasticity of fibers and films by sound velocity measurements. J. W. Ballou and S. Silverman. **16:** 100—1944

11.4 Radiation from Vibrating Objects. Acoustical Impedance. Mechanical Impedance. (See also 5.3)

PAPER

Acoustic intensity distribution from a "piston" source. A. O. Williams and L. W. Labaw. **16:** 231—1945

Effect of radiation on the vibrations of a circular diaphragm. Melvin Lax. **16:** 5—1944

On the theory of the directional patterns of continuous source distributions on a plane surface. R. Clark Jones. **16:** 147—1945

Wide range adjustable acoustic impedance. Willard F. Meeker and Frank H. Slaymaker. **16:** 178—1945

ABSTRACT

Theorem on directivity patterns. R. Clark Jones and L. A. MacColl. **16:** 101—1944

Wide-range adjustable acoustic impedance. Willard F. Meeker and Frank H. Slaymaker. **16:** 102—1944

11.5 Sounds of Finite Amplitude. Distortion

PAPER

Action of a direct radiator loudspeaker with a non-linear cone suspension system. Harry F. Olson. **16:** 1—1944

Production of inharmonic subfrequencies by a loudspeaker. R. V. L. Hartley. **16:** 206—1945

ABSTRACT

Action of a direct radiator loudspeaker with a nonlinear cone suspension system. Harry F. Olson. **16:** 100—1944

11.6 Sound in Tubes

PAPER

Attenuation of sound in lined ducts. Charles T. Molloy and Esther Honigman. **16:** 267—1945

Propagation of sound in lined ducts. Charles T. Molloy. **16:** 31—1944

Reflection of sound due to a change in cross section of a circular tube. John Miles. **16:** 14—1944

ABSTRACT

Propagation of sound in lined ducts. Charles T. Molloy. **16:** 102—1944

11.7 Theory of Waves and Vibrating Systems. (See also 5.4)

PAPER

Action of a direct radiator loudspeaker with a non-linear cone suspension system. Harry F. Olson. **16:** 1—1944

Effect of radiation on the vibrations of a circular diaphragm. Melvin Lax. **16:** 5—1944

Recording Lissajous figures. Wayne B. Hales. **16:** 137—1945

Singing flames. Arthur Taber Jones. **16:** 254—1945

Supersonic transmission at oblique incidence through a solid plate in water. J. B. Smyth and R. B. Lindsay. **16:** 20—1944

ABSTRACT

Sound wave fields within cavities. Richard K. Cook. **16:** 102—1944

Table of the Bessel functions $J_0(Z)$ and $J_1(Z)$ for complex arguments. Prepared by the Mathematical Tables Project of the Work Projects Administration of the Federal Works Agency. **16:** 81—1944

Theorem on directivity patterns. R. Clark Jones and L. A. MacColl. **16:** 101—1944

Transients in linear systems. Volume I. Murray F. Gardner and John L. Barnes. **16:** 80—1944

SUBTITLE

Frequency response of a Helmholtz resonator. **16:** 124—1944

12. General, Unclassified

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